FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Paths to a Climate-Neutral Energy System

The German Energy Transition in its Social Context

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Foreword

The study “Paths to a Climate-Neutral Energy System – The German Energy Transition in its Social Context” was conducted by the Fraunhofer Institute for Solar Energy Systems ISE as an in-house research project. Part of the work for this study was performed within the Kopernikus ENavi project, financed by the German Federal Ministry of Education and Research. The main motivation behind the study was to investigate how specific social behavior and attitudes influence the course of the energy transformation and what effect this has on the investments and costs required for the transition of the German energy system.

We would like to thank all the employees of Fraunhofer ISE who assisted in this study. This group of participants is far larger than the authors named on the title page. The vast expertise on the development of the future costs and performance of significant technologies within the institute was extremely important and helpful and provided a solid basis for the simulations.

With the analysis and results presented here, we hope to make a valuable contribution to an objective, factual discussion on the feasibility of a climate-neutral energy system, based on the use of renewable energy and the provision of higher efficiency for energy conversion and utilization.

Freiburg, Germany
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Hans-Martin Henning   Andreas Bett

Summary

In this study, potential development paths for the German energy system were examined, which lead to a reduction of at least 95 % of energy-related CO_2 emissions, compared to 1990 levels, by 2050. Two additional scenarios with the aim of achieving 100 % reduction in energy-related CO_2 emissions by 2050 were also considered.

Besides the questions of technical feasibility and costs, societal behavior plays a significant role in determining whether and in what form the energy transition can be implemented. To take this aspect into account, four main scenarios, each describing different behavior and attitudes of society, were analyzed. The societal aspects play a dominant role in the various scenarios and thus set the framework for the further development of the energy transition.

The *Persistence* scenario is characterized, in particular, by strong resistance to the use of new technologies in the private sector. The *Non-Acceptance* scenario is defined by a lack of acceptance among the population for the further expansion of large infrastructures. By contrast, the *Sufficiency* scenario describes a development in which behavioral changes are visible in a large majority of the population, resulting in a noticeable decrease in energy demand. These three scenarios are compared to the *Reference* scenario, in which no conditions to either promote or impede achieving the climate targets are specified.

The simulation and optimization of the various scenarios are carried out using the energy system model REMod (Renewable Energy Model). This model was developed almost ten years ago by the Fraunhofer Institute of Solar Energy Systems ISE and since then has been intensively further developed and optimized.

The most important results and findings derived from the simulations are as follows:

1.
From a technical and systemic point of view, the achievement of the climate protection targets in the German energy supply is feasible on the basis of renewable energy sources.

Using dynamic simulations carried out in hourly time steps from 2020 up to 2050, the model showed that a secure energy supply is guaranteed hour-by-hour in all consumption sectors despite a high share of variable renewable energy sources in the electricity mix. At the same time, the results from the various scenarios demonstrate that the differences in expenditure and costs are strongly dependent on the framework conditions.

2.
Electricity from renewable energy sources will dominate the energy supply, with wind and solar being the largest primary energy sources.

In the scenarios considered, the total installed capacity of wind and photovoltaic power plants combined lies between 500 GW_{el} and over 750 GW_{el} in 2050, or about five to seven-fold of the installed capacity today. All of the development scenarios considered show that solar and wind power plants shall cover between 50 % and 60 % of the primary energy demand in 2050.

3. Due to lower losses in the conversion chains, mostly as a result of sector coupling, the primary energy consumption decreases significantly.

In the investigated scenarios, the primary energy consumption for the energy sector in 2050 lies between 1750 TWh (*Sufficiency* scenario) and 2500 TWh (*Persistence* scenario), thus appreciably lower than today's value (almost 3400 TWh). This is despite the assumed increase in useful energy consumption over time considered in most of the scenarios. The reduction is mostly due to a more or less pronounced displacement of combustion-based technologies (boilers, thermal power plants, internal combustion engines) by electricity-based technologies and the resulting improvements in conversion efficiency throughout all sectors. Therefore, sector coupling, i.e. the increased direct – or in the case of synthetic energy carriers produced by renewable electricity – indirect use of electricity, is a key element of the energy system transformation throughout all consumption sectors.
Considering the above (points 2 and 3), it can be concluded that the core building blocks needed for reaching the CO_2 emission targets in the most cost-effective manner are: the successive reduction of fossil fuel use in the heat (building, processes) and transport sectors in conjunction with a greater use of electricity and an accelerated reduction of specific emissions from electricity generation.

4. Greater flexibility in the generation and use of electricity becomes a key element of the system development

The growing share of variable renewable energy sources for power generation necessitates a paradigm shift in the supply model. The predominantly demand-based power supply relying on large power plants is increasingly being replaced with a system in which continuous energy balancing is carried out between energy supply from renewable energy sources, characterized by limited controllability and predictability, and a consumption that should be as flexible as possible. This results in a complex interplay between energy supply and time-adjusted (through load shifting, demand response) energy consumption, including stronger coupling of the electricity, heat and transport sectors as well as temporary use of flexible production systems such as electrolyzers for hydrogen production and storage systems of all types.
Multimodal heating networks fed from different generators in combination with large heat storage units have also proved to be an effective measure for flexibility and load management, especially in dense urban areas.
Stationary battery storage facilities are another important element of flexibility. For the scenarios investigated the installed capacity of battery storage in 2050 lies between 50 GWh_{el} and 400 GWh_{el}.
Last but not least, controllable power generators are also needed in the long term, especially highly flexible gas turbines with a total installed capacity between 100 GW_{el} and over 150 GW_{el}.

5. Electrolysis combined with hydrogen utilization for various applications is a key building block of the future energy supply.

Electrolyzers can be used to produce electricity-based energy carriers such as hydrogen, methane or liquid fuels, making them an important option for renewable electricity use. Although these plants achieve higher full-load hours at foreign locations with a higher availability of renewable power than Germany, their installation in Germany has proved advantageous in the context of a cost-optimized energy system transformation. There are three main reasons for this: Firstly, the secondary energy carriers produced can be used in applications where a direct use of electricity is difficult to implement. Examples of this are liquid fuels for maritime transport, air traffic or heavy-duty transport as well as hydrogen and hydrocarbons for the chemical industry.

Secondly, those electrolyzers that enable rapid start-up and shut-down can be used as flexible loads, thus furthering the potential for integrating renewable electricity into the energy system.
Thirdly, these processes offer the possibility of producing electricity-based energy carriers from renewables during times of high electricity feed-in. These secondary energy carriers can then be stored nearly loss-free over a period of several days or months. Subsequently they can be used, for example, in dispatchable power plants when grid feed-in from renewable electricity is low. Thus, a reliable power production is guaranteed without the use of fossil fuels. For the scenarios investigated, the installed capacity of electrolyzers ranges between around 50 GW_{el} and 120 GW_{el} in 2050.

6.
The efficient use of energy and a reduction in consumption resulting from implemented technical measures contributes significantly to reaching the climate targets, especially in the area of heat provision.

In all of the investigated scenarios, increasing the rate of energy retrofits in buildings was shown to be an important factor in decreasing the space heating requirement. This goes hand in hand with the conversion of many heating systems to a lower temperature level, which accommodates the use of heat pumps and solar thermal systems. There are also numerous possibilities in the industry for more efficient energy utilization, which in part can be realized by the direct use of electricity.

7.
Behavioral changes in a majority of society that result in greater energy conservation can have a significant effect on the restructuration of the energy system and substantially reduce costs.

In the *Sufficiency* scenario, a development was investigated in which behavioral changes in a large part of society resulted in considerable reductions in energy consumption. A shift in values, driven by a growing awareness of the dangers posed by climate change, could bring about such behavioral changes. If this were to occur, a significantly smaller number of technical systems for the conversion, storage, distribution and consumption of renewable energy would be required. As a result, the necessary investments and costs would be lower. With an average value of about 50 € per tonne CO_2 over the next thirty years, the carbon avoidance costs in this scenario are far lower than for all other models calculated in this study. At the same time, it can be assumed that smaller expansion of renewable energy plants and other technical facilities in the energy system would also lead to greater acceptance of the changes associated with the energy system transformation.

8.
The import of energy in the form of electricity and synthetic chemical energy carriers produced abroad with renewable electricity is an important part of reaching the German climate protection targets.

In the scenarios investigated, the amount of imported synthetic chemical energy carriers produced with renewable electricity abroad and consumed in 2050 varies between ca. 75 TWh (*Sufficiency* scenario) and 500 TWh (*Persistence* scenario). Naturally, these values are strongly dependent on the assumed price development for such energy carriers. Although the absolute quantities are subject to a great deal of uncertainty, the large difference resulting from different social behavior and attitudes is clear. In particular, an adherence to the use of familiar combustion-based technologies for heat supply and transport (*Persistence* scenario) results in large import quantities of such energy carriers.

9.
From a system perspective, it would be possible to increase the use of photovoltaics if wind capacity is not expanded to its optimal level. However, this would lead to a greater need for energy storage and also to higher CO_2 avoidance costs than would be the case for a cost-optimal development.

In the *Reference* scenario, which assumes cost optimization without external intervention, total onshore and offshore wind capacity is around 40 % (263 GW_{el}) and photovoltaic capacity is around 60 % (414 GW_{el}) of the total installed capacity of plants generating electricity from variable renewable energy sources. This means that about two thirds of the total electricity generated by these plants is from wind turbines and around one third from photovoltaics. On the other hand, in the *Non-Acceptance* scenario, which is characterized by a strong resistance to further expansion of large infrastructures, the total installed wind capacity (on and offshore) is 115 GW_{el} while the photovoltaic capacity increases to 645 GW_{el}. As a result, a number of different measures are required to integrate the increased solar power into the energy system in a useful way also for periods of high solar radiation in Germany. For example, the orientation of photovoltaic installations shall be distributed from east to west in order to widen the feed-in profile over the course of the day and avoid an extreme midday peak. At the same time, with 400 GWh_{el} of installed capacity considerably more stationary battery storage units will be installed by 2050 than in the *Reference* scenario (150 GWh_{el}). Furthermore, there will be 300 TWh of imported chemical energy sources, i.e. around twice as much, and the average CO_2 avoidance costs will increase from around € 150 per tonne (*Reference* scenario) to € 162 per tonne over the entire period under consideration.

10.
The transformation of the energy system involves additional costs compared to a development that is not oriented towards compliance with climate protection targets. A large part of these additional costs are for investments that are necessary for the development and reconstruction of the energy system..

Compared to a Business-as-Usual (BAU) scenario, the net additional expenditures range between € 440 billion for the *Sufficiency* scenario and € 2330 billion for the *Persistence* scenario. These results underline that societal behavior and attitudes have a significant influence on the costs associated with the transformation of the energy system towards a climate-neutral energy supply. In the scenarios, the annual additional expenditures range from 0.4 % (*Sufficiency* scenario) to around 1.5 % (*Reference* and *Non-Acceptance* scenarios) to around 2 % (*Persistence* scenario) of Germany's 2019 gross domestic product (GDP). Another comparative measure for the annual additional costs is the turnover attributed to the Christmas business, which in Germany for 2019 was just under € 102 billion, i.e. about twice as high as the average annual expenditure for the energy system transformation in the *Reference* and *Non-Acceptance* scenarios.
The results show that in almost all scenarios far more than half of the additional expenditure is incurred for investments necessary for restructuring the energy system. Once this system transformation is (for the most part) completed in 2050, investments will decrease significantly, since from then on only replacement investments will be necessary.
When considering costs, it should also be noted that the analysis carried out here did not consider external costs for the different scenarios, nor did it consider the total macroeconomic impact, which include added value and employment effects. In particular, it does not take into account the costs and effects associated, for example, with a sharp rise in atmospheric temperature that would result if climate protection targets are not met.

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1
Introduction

Globally occurring phenomena such as forest fires on an unprecedented scale, storms, melting glaciers and the dramatic decline in glaciation in the northern polar region provide strong indications of changes in the global climate that are very likely attributable to climate change. At the same time, especially teenagers and young adults in many countries and regions of the world are raising their voices with Fridays for Future and calling for a massive policy changes and effective measures to significantly reduce the climate-relevant trace gas emissions worldwide. It is becoming clear that an 80 % reduction in greenhouse gas emissions in Germany compared with 1990 levels by the middle of the century will not be sufficient. More stringent reductions are necessary from Germany in order to achieve the climate goals agreed upon in December 2015 Paris accord and thus limit the global temperature increase to an average of 2 °C, or better 1.5 °C, compared with pre-industrial levels. The European Commission, newly formed in 2019, has also increased the European Union's climate protection targets, and the so-called "European Green Deal" aims to achieve a climate-neutral Europe by 2050 [1].

The energy transition is a highly complex and ambitious large-scale project that mandates a substantial restructuring of the present energy supply. In this study, we examine possible development pathways for the German energy system starting from today up to the middle of the century that comply with the ambitious goals mentioned above. To this end, this study examines scenarios that lead to a reduction of energy-related CO_2 emissions by 95 % and 100 % by 2050 (and in one case also by 2035) compared to the 1990 level. Today energy-related CO_2 emissions account for around 86 % of total German greenhouse gas emissions. Therefore, restructuring the energy system to achieve a climate-neutral energy supply, the so-called "Energiewende" is the most important measure towards reaching comprehensive climate neutrality. The results of this study relate only to energy-related CO_2 emissions, since the simulation and optimization model REMod used to calculate possible transformation paths maps only the energy sector fully.

It is becoming increasingly obvious that, in addition to questions of technical feasibility and costs, societal behavior plays a decisive role in whether and in what form the energy transition can be implemented. Public attitudes vary over a broad spectrum: On the one hand, more and more people are taking on behavior and lifestyles that follow the most economical use of energy and the lowest possible greenhouse gas emissions. On the other hand, in many places resistance is emerging to the further expansion of wind power or electricity grids, i.e. infrastructures that are imperative for the successful transformation of the energy system. Different trends can be observed even in private investment decisions, which have significant consequences for energy consumption and CO_2 emissions and are often based on reasons beyond purely economic considerations. These range from a rather persistent behavior that resists the use of new technologies (e.g. for the supply of heat to buildings and in motorized private transport) up to initiatives, on the other hand, calling for energy efficiency measures or the installation of renewable energy systems on the private, community and civic levels.

In order to take this aspect into account, we have based the four main scenarios in this study on different narratives in which certain behaviors and attitudes play a dominant role. These provide then the framework for the development of the energy transition. The *Persistence* scenario is characterized, in particular, by a strong resistance to the use of new technologies in the private sector, e.g. by an insistence to combustion technologies both for the heat supply of buildings and for motorized private transport. The *Non-Acceptance* scenario is characterized, above all, by strong resistance to the further expansion of large infrastructures, especially wind turbines and electricity grids, but also, the installation of overhead contact lines above the autobahn, for example. The *Sufficiency* scenario describes a development in which behavioral changes take effect in large parts of society, resulting in a noticeable reduction in energy consumption. A widespread change in values, driven by a growing awareness of the dangers posed by climate change, could, for example, bring about such behavioral changes. These three scenarios are contrasted with a scenario in which no specific conditions are defined that would promote or impede achievement of the climate targets (*Reference* scenario).

To simulate and optimize the scenarios described above, REMod (Renewable Energy Model) is used for the calculations. This model was created almost 10 years ago at the Fraunhofer Institute for Solar Energy Systems ISE and has been intensively developed since then. REMod has been used to carry out numerous studies and analyses for various clients, including model calculations for sector coupling within the framework of the BMBF-funded academy project ESYS (Energy Systems of the Future).[1] Since the publication of the study "What Will the Energy Transformation Cost?" in 2015, significant extensions have been added to the model, e.g. in the area of industrial processes. Since more and more new technologies are reaching market maturity or are expected to do so in the near future, REMod's technology portfolio has been expanded and refined in step with these developments. For example, the cost and efficiency curves of all technologies were adapted to current market analyses and the state-of-the-art research. For power plants and several other system components, an optimized start-up behavior was mapped in the model. In addition to the detailed mapping of demand sectors, mapping the imports of CO_2-neutral energy sources from abroad was improved. The available weather data sets were increased to five, making the results more robust with regard to different weather conditions with extreme events.

Following this introduction, the study is divided into two main chapters. The methodological approach is described in Chapter 2. This includes a short presentation of REMod, followed by the prescribed paths for the reduction of energy-related CO_2 emissions up to 2050. Then the scenarios mentioned above and the assumptions and boundary conditions on which they are based are described. Chapter 3 provides a detailed presentation of the results. In Chapter 3.1, the transformation paths in the various scenarios are compared, followed by an analysis of the results for the different consumption sectors (industry, transport, building heating) in Chapter 3.2. The results from these scenarios are based on a 95 % reduction in energy-related CO_2 emissions by 2050, compared to 1990 levels. For two additional scenarios, calculations were carried out that model a complete, or 100 %, reduction of energy-related CO_2 emissions by 2050 and 2035 respectively (Chapter 3.3). Finally, a cost analysis was performed for all six scenarios, ending with a calculation of the CO_2 avoidance costs (Chapter 3.4).

A detailed appendix with data on the performance and cost developments of all the technologies used in the model calculations as well as other data included in the calculations is available on the Internet.[2]

1 The position paper "Sector Coupling - Options for the next phase of energy system transformation" and the analysis "Sector Coupling - Studies and reflections on the development of an integrated energy system", published in 2017. Download at https://energiesysteme-zukunft.de/themen/sektorkopplung

2 For more information, see: https://www.ise.fraunhofer.de/klimaneutrales-energiesystem and https://www.energy-charts.de

2
Methodology

The objective of the scenarios is to describe possible, consistent future developments based on currently available knowledge, but not to predict future developments. The transformation paths shown as the result of model calculations are based to the best of our knowledge on the technologies available today and their cost and performance projections. The main aim of modeling is to analyze, from a systems engineering perspective, the development of overall systems that are constrained by a fixed upper limit on emissions and to determine their associated costs. The optimization algorithm calculates the development paths that lead to the lowest possible total costs. The configuration of the energy system that is calculated can vary to a greater or lesser extent depending on the set boundary conditions. To take the associated uncertainties into account, several consistent scenarios are defined and analyzed. In this way, the effects of the specified boundary conditions on the energy system can be shown, robust technological developments identified, and recommendations for action derived. In contrast, the model does not allow for any statements to be made about the appearance of future business models for market participants, how prices will be set or how costs will be distributed among different social groups.

The Renewable Energy Model (REMod) developed by the Fraunhofer Institute for Solar Energy System ISE was used to calculate the scenarios in this study. The basic idea of the model is to identify technically and economically feasible transformation paths for the German energy system. At the same time these paths shall comply with the climate policy goals as defined for reducing energy-related CO_2 emissions. By simultaneously optimizing all sectors of the energy system (electricity, building heating, industrial process heat and transport), the mutual influence of these sectors is taken into account. All relevant energy sources, converters, storage facilities and all consumption sectors are mapped in the model. The aim of the calculations is to describe for each scenario a cost-optimized path for the transformation of the current energy system until 2050, as defined by given boundary conditions and parameters. The final CO_2 reduction target (e.g. 95 % reduction compared to 1990) is defined by a CO_2 path given for each year. This CO_2 path represents the upper limit of permitted CO_2 emissions and is a fundamental boundary condition for optimization. This chapter describes the structure and functionality of the model as well as the input data and the specific assumptions and boundary conditions relevant for constructing the scenarios.

2.1 The Renewable Energy Model

A central feature of REMod is the simultaneous optimization of all consumption sectors of the energy system with a high temporal resolution [2, 3]. The simulation considers all hours, from today up to 2050. The calculated scenarios represent the technically possible, cost-optimized transformation paths of the German energy system that comply with a given CO_2 reduction path up to 2050. In addition to assumptions on the development of the various sectors, plausible development forecasts on the costs and efficiencies of the considered technologies are stored. To create the scenarios, the model optimizes the energy system development based on the available technologies so that all given boundary conditions are met while simultaneously optimizing the costs to the greatest extent possible. The hourly calculation ensures that all converters, storage devices and consumers are dimensioned in such a way that each consumption sector is supplied every hour with sufficient energy. For the optimization, technical components are accordingly removed or replaced by alternative components (e.g. oil-fired boilers by heat pumps), taking their expected service life into account. The consideration of different historical weather data (five years with hourly values of all the relevant variables) ensures a statistical range that includes weather extremes, e.g. years with longer phases of low renewable energy availability.

Figure 1 shows a schematic overview of the model, which illustrates the most important energy conversion technologies and consumption sectors. They are broken down into the main forms of (traditional) electricity applications (e.g. lighting, information and communication technology, refrigeration, mechanical energy), building heating (space heating, domestic hot water), transport and industrial process heat.

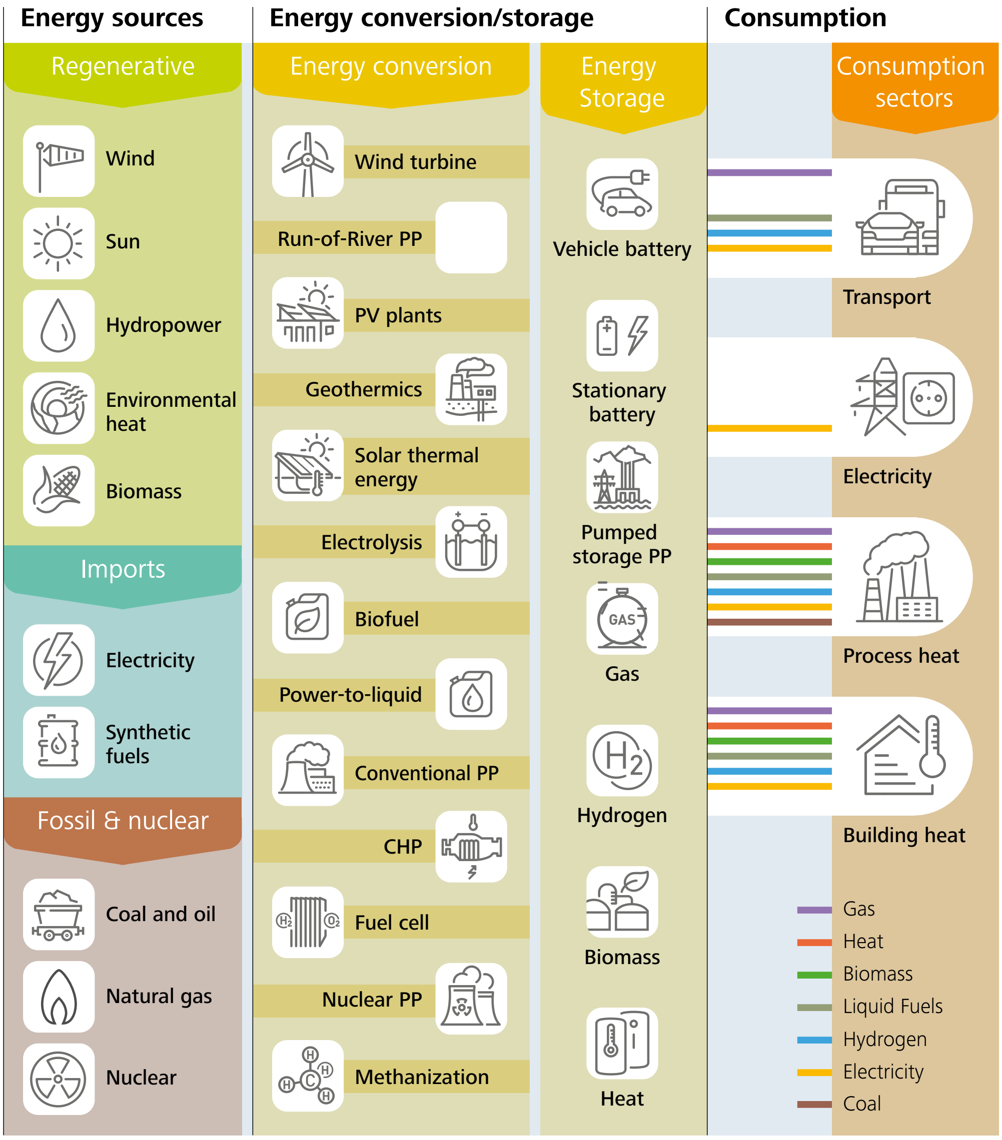


Figure 1: Schematic representation of the REMod model (PP: power plant, CHP: combined heat and power generation) [3].

The input data used for the calculations are divided into two groups of different time resolutions. Five data sets based on real weather data for the years 2011 to 2015 are stored as hourly profiles. These describe, among other things, the temporal course of outdoor temperature, solar irradiation, feed-in profiles of weather-dependent renewable energy sources, process heat demand or driving profiles in the transport sector. The second database contains the technical and economic parameters of technologies and energy carriers as well as boundary conditions for each year from 1990 to 2050. The inventory of the German energy system is given from 1990 to 2019 and includes, e.g. age, efficiency and installed capacity or number of power plants and other energy converters, storage facilities, heating technologies in buildings as well as the number of buildings and vehicles. For the optimization process carried out in the model between 2020 and 2050, assumptions about the development of the costs and efficiency of all available technologies as well as their technical life time are used as input. Additionally, the cost development of fossil fuels and of energy carriers produced abroad using renewable energy sources are assumed on a yearly basis.

Based on this database, the future **development of the plant fleet** across all sectors will be optimized. This optimization includes conventional power plants, variable renewable electricity generators, electrical storage facilities, thermal and chemical energy carriers, the vehicle fleet divided into cars and trucks with different powertrain technologies as well as different technologies for converting electricity into hydrogen (H_2), methane (CH_4), liquid fuels or heat. The optimization is based on the assumption that all technical equipment will be replaced at the end of its specified life time. At this point, the optimization algorithm decides whether, for example, in the space heating sector, a gas boiler shall be replaced by another gas boiler or, rather, e.g., by a heat pump. The power plant fleet is simulated using an iterative optimization process constrained by boundary conditions based on the security of supply (the energy balance must be met every hour), **climate protection** (the CO_2 path must comply with the specified target values) and **economic efficiency** (lowest possible costs for the entire optimization period from 2020 to 2050).

The **final energy demand** is divided accordingly into the four sectors: building heating (space heating, hot water), traditional electricity applications, industrial process heat and transport.

In REMod, the hourly demand for **space heating and hot water** in the building sector is calculated according to DIN EN 13790 [4] using the so-called "Simply-Hourly-Method", or SHM. Within this sub-model a distinction is made between residential and non-residential buildings that are subdivided into a total of 19 characteristic building types. In total there are nine classifications for residential buildings (three age classes multiplied by three building types) and ten classifications for non-residential buildings. The input data used are the weather data from 2011 to 2015, building cubature, average living space or useful area per building type, number of buildings and age-dependent heat transfer coefficients. The values from the German industrial standard DIN EN 13790 are used for the energy efficiency and the calculation of the building energy demand.

For space heating supply, a distinction is made between two classes of **heating systems** with their corresponding temperature levels (standard heating system with radiators, low temperature heating e.g. radiative heating). When combining these with the eleven technologies for supplying heat, there are twenty different heat supply options for the building sector. The available heat supply technologies include conventional boilers based on methane, biomass or oil, engine-driven combined heat and power (CHP) units, electrical, fuel-based and hybrid heat pumps (with air or ground as heat source) and fuel cell systems based on methane or hydrogen. All technologies can be optionally supplemented with hot water storage tanks and solar thermal collectors.

In addition to these systems, the model also includes the option of supplying heat via heat grids. These can supply heat from geothermal or CHP plants, large electric heat pumps, (peak load) gas boilers or also solar thermal collectors. In addition, large thermal energy storage systems can be used in heat grids. Many of these technologies have the ability to react flexibly to the requirements of the overall system. For example, if power availability is low at a certain time, the thermal energy storage can be discharged instead of operating large electric heat pumps. Conversely, large electric heat pumps may be put into operation if there is a particularly high feed-in from photovoltaic or wind energy systems during the hour under consideration. In this case, electric heat pumps or simple heating rods can also be used to raise the temperature in thermal energy storage systems.

Traditional electricity applications describe the load occurring in the network today[3] excluding the electricity demand for heat and road transport. The load profiles in the model are based on data from the European Network of Transmission System Operators for Electricity (ENTSO-E), which also includes the electricity demand of rail transport and

3 *Reference* is hereby made to the year 2016, as the relevant statistical values are available for that year.

the mechanical energy industry. In addition to the base electricity load, the model also takes into consideration additional electricity consumption in the course of future system development, such as battery electric vehicles or electric heat pumps.

The **electricity generators** implemented are conventional power plants using lignite and hard coal as fuel, nuclear power plants (until their phase out in 2022), oil-fired power plants, gas turbines (with CH_4 or H_2 fuel), CHP plants, combined cycle gas turbine plants (CCGT) and fuel cell systems based on hydrogen or methane. Renewable electricity can be generated from onshore and offshore wind, photovoltaic and run-of-river power plants. Photovoltaic plants are divided into three different types: ground-mounted systems facing south and roof-mounted systems facing south, east or west. The differing costs (ground-mounted are cheaper than roof-mounted systems) as well as various feed-in profiles based on orientation are considered. In addition, depending on the parameterization, different interconnections are available for the import and export of electricity.

The **energy demand for transport** is first converted into traction energy (kinetic energy necessary for the movement of vehicles) on the basis of BMWi data and then distributed to each hour of the year using hourly resolved travel or demand profiles. The simulation model then determines the final energy demand for the respective fuels or electricity using the efficiency of the respective powertrain technologies. The energy demand for aviation and shipping[4] as well as fuel-based railway traffic are also taken into account in the balance. The transport sector is represented in detail by passenger cars and trucks (only one class size each), which are each described by seven drivetrain concepts and the corresponding energy demand. In addition to the currently established combustion engines using gasoline, diesel or methane as fuel, battery and hydrogen-electric (fuel cell) powertrain concepts are implemented. All concepts can also be part of the solution as plug-in hybrid variants. In addition to the powertrain concepts mentioned above, overhead-line trucks can be used as an option for freight transport, depending on the scenario framework. Battery-powered powertrain concepts can be used to increase flexibility in the system, i.e. as electricity storage that can be charged or discharged to provide grid support. The degree of usability of this flexibility option is determined by a predefined proportion of users, who allow flexible control of the battery up to a specified maximum depth of discharge.

Energy used to provide **process heat in industry** is divided into different temperature levels. For the temperature range below 500 °C an hourly demand profile close to the base load is assumed. For applications with a temperature higher than 500 °C, a constant energy demand is assumed. The total energy demand over one year is based on data from the BMWi [5] and assumptions specific to each scenario.

The energy system can use **electrical energy storage** devices in the form of stationary and mobile batteries in vehicles or pumped storage power plants. In addition, hydrogen storage and thermal hot water storage of various sizes are taken into account. For methane storage, the simplified assumption is made that the storage capacities already existing today (including the grid, approx. 210 TWh [6]) will continue to be available to the system in the future. Their future size is therefore not a result of the optimization.

Hydrogen can be used in transport, industry (materially or energetically to generate process heat) or in buildings (by means of H_2 fuel cells). In addition to feeding it into the natural gas grid, the use of hydrogen is an option for re-generating electricity in gas turbines. Furthermore, hydrogen can be converted in methanation or Power-to-Liquid plants into synthetic natural gas or liquid fuels respectively for use in power plants, heating technologies or for transport. Hydrogen can either be imported or produced domestically from biomass, by steam reforming of methane or by electrolysis from renewable energy. The capacities of the respective technologies are determined in the model within the scope of the optimization.

4 The energy demand of aviation covers the aviation fueled in Germany. The energy demand of shipping only includes domestic German transport.

Biomass can be used either directly or after conversion into another energy source. For example, wood can be used in boilers to provide process heat for industry or to generate low-temperature heat in the building sector. In addition, biogas plants, gasification plants with subsequent synthesis into hydrogen, methane or liquid fuels as well as biodiesel plants are implemented for the conversion of biomass.

In addition to domestic production, **synthetic energy carriers** produced from renewable energy sources can be imported from abroad. Among these energy carriers are hydrogen, methane and liquid fuels. A maximum available quantity with a specific price is specified as an annual assumption. The specific price is based on the production costs and the costs necessary for transporting the energy carrier. The amount of the available quantity that is actually used each year is determined by the optimization in the model.

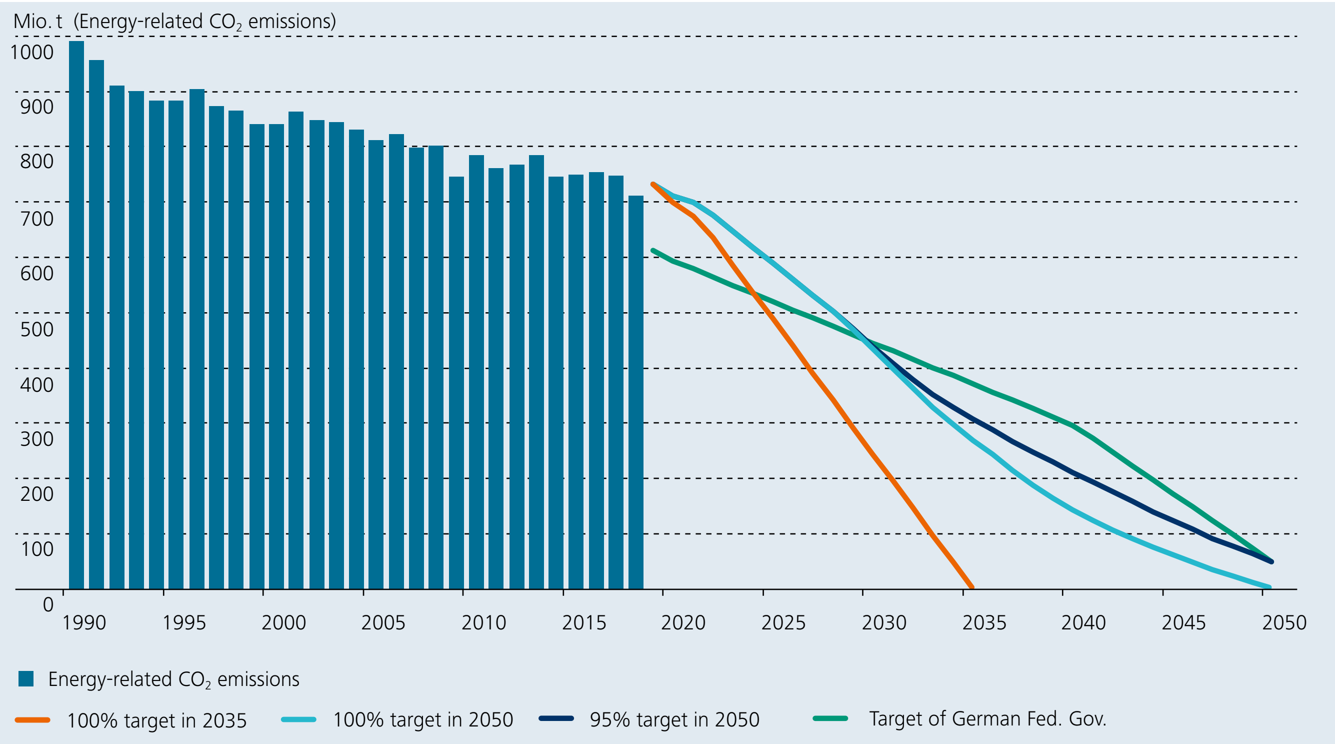
The **mathematical optimization** identifies cost-optimized transformation paths that comply with the given boundary conditions such as the upper limit of permissible CO_2 emissions and other scenario-dependent conditions. The algorithm used for this purpose is the so-called Covariance Matrix Adaptation Evolution Strategy procedure [7]. The term **"cost optimization"** requires an explanation here: The calculations take all investments for new plants and for the replacement of old plants (replacement investments) into account as well as the corresponding capital costs (assumed interest rate of 7 %). The operating and maintenance costs for all components are also considered. Finally, costs for cultivated biomass and imported energy carriers (electricity, fossil fuels and synthetic fuels produced abroad from renewable energy sources) are included. The cost calculation is based on an annuity method, whereby all payments are discounted in the future (assumed discount rate of 2 %). For each of the scenarios investigated, the cumulative expenditure (investments and costs) for the reconstruction, expansion and operation of the total energy system for the period from 2020 to 2050 is determined and then minimized in the optimization process.

2.2
Setting the Climate Policy Targets

The model calculations in this study are based on the CO_2 reduction targets of the German government. Since the modeling only addresses the energy sector, only energy-related CO_2 emissions are included in the balance. A reduction of energy-related CO_2 emissions by 95 % compared to 1990 levels was set as a minimum target, since this reduction is most compatible with the European Commission's Green Deal goal of a climate-neutral Europe by 2050. Additionally two scenarios were calculated in this study that consider zero energy-related CO_2 emissions (100 % mitigation) by 2050.

In 2019, CO_2 emissions in Germany were 35 % lower than in 1990.[5] It is therefore unlikely that in 2020 the target of a 40 % reduction in CO_2 emissions compared to 1990 levels will be be met [8]. To account for the resulting additional emissions, we used a combination of a CO_2 reduction path and a CO_2 budget in this study. The reduction path is set so that CO_2 emissions are reduced linearly from 2020 to 2030 in order to meet the reduction target of 55 % by 2030. This means, however, that more emissions are released in the period from 2020 to 2030 than would have been the case if a reduction to 40 % had already been achieved in 2020 (see Figure 2, area between the blue and green lines between 2020 and 2030). To compensate for these additional emissions, we adjusted the CO_2 reduction target for 2040 and the CO_2 reduction path from 2030 to 2050 so that the path is steeper than in the original plans of the German government. As a result, the sum of emissions from 2020 to 2050 is equal to the sum in the federal government's Energy Concept 2010 for a target of 95 %.

Figure 2: Historical development of energy-related CO_2 emissions [5]; The German federal government's CO_2 reduction targets of 95 % compared to 1990 levels [9] and the targets considered in the study up to 2050.



5 Achieved reduction of emissions in 2019 is based on [5]. Final values determined by the Federal Environment Agency are not yet available for this year.

2.3
Construction of Consistent Scenarios

The current climate policy debate in Germany shows that the energy transformation is not only a question of technical and economic feasibility, but also of social and political will. In order to include effects of influencing variables such as consumer behavior, insistence on using today's technologies or willingness to change, acceptance of infrastructural changes as well as aspects of sufficiency and reduction of consumption, four scenarios with a CO_2 reduction target of 95 % are defined. In addition, two further scenarios are presented with a CO_2 reduction target of 100 %, which are derived from the main scenarios. The central assumptions for these scenarios and their corresponding names, which are used hereafter, are shown in Table 1.

Table 1: Description of key boundary conditions in the scenarios examined

	Reference	**Persistence**	**Non-Acceptance**	**Sufficiency**	**Reference100**	**Sufficiency2035**
CO_2 Reduction Targets	95 %	95 %	95 %	95 %	100 %	100 %
Upper Limit for Installed Capacity in GW_{el}						
Photovoltaics	530[6]	530	800[7]	530	530	530
Wind Onshore	230	230	80	230	230	230
Wind Offshore	80	80	40	80	80	80
Electricity imports	40	40	20	40	40	40
Development in Consumption						
Traditional electricity applications	constant	constant	constant	decreasing	constant	decreasing
Transport volume / Guidelines	increasing	increasing some internal combustion	increasing without overline trucks	decreasing	increasing	decreasing
Heated Building Spaces / Guidelines	increasing	increasing Some gas boilers	increasing	decreasing	increasing	decreasing
Process Heat	slightly declining	slightly declining	slightly declining	decreasing	slightly declining	slightly declining

The scenarios listed in Table 1 are described in more detail below. For all of the scenarios (except the *Reference* scenario), only the assumptions that differ from the *Reference* scenario are explained.

6 The 530 GW limit is made up of 143 GW for ground-mounted systems and 387 GW for roof-mounted systems. These values are based on the studies [10, 11]. However, there are different analyses of land potential, from which other potential limits can also be derived..

7 According to a bottom-up analysis of the German building stock (residential, commercial) carried out at KIT, roof areas in particular have a significantly higher potential than that indicated in almost all other sources [12]. For the Non-acceptance scenario, the available potential was therefore increased to a total of 800 GW, of which 190 GW are for ground-mounted systems and 610 GW for roof-mounted systems..

2.3.1 *Reference* Scenario

In the *Reference* scenario, the cost-optimal transformation of the energy system is examined without assuming pronounced social behavior with regard to acceptance of change or altered consumption. The main assumptions that characterize this scenario are listed below by sector:

Energy Supply: The technical installation potential of photovoltaic systems totals 530 GW_{el}. This consists of 143 GW_{el} ground-mounted systems and 387 GW_{el} roof-mounted systems, which can be oriented to the south or east and west. The installation potential for onshore wind turbines was set at 230 GW_{el} [13]. A high potential of 80 GW_{el} was assumed for the offshore wind energy installations. Coal-fired power generation will be phased out by 2035[8] and nuclear power by 2022 [14]. The interconnector capacity for electricity imports will increase from just under 17 GW_{el} today to 40 GW_{el} in 2050 [15]. Synthetic fuels (hydrogen, methane and liquid energy carriers) produced abroad from renewable electricity can be imported as of 2030.

Electricity Sector: The electricity demand for lighting, cooling, information and communications technology (ICT) and mechanical energy is constant up to 2050.

Transport: Moderate development. By 2050, the total mileage of motorized private transport will increase by 3.5 % and that of road freight transport by 27 % [16]. An overhead-line infrastructure is being built for electrified freight transport. Battery electric vehicles cannot exceed 80 % of the annual new registrations.[9] 10 % of all users agree with the flexible control of their car battery (grid-to-vehicle G2V, vehicle-to-grid V2G) to balance the electricity load [17]. Air traffic, which is recorded in the balance sheet, will remain constant until 2050.

Building Heat: Moderate development. Heated living area in Germany will increase by a total of 8 % between today and 2050 [18]. Heat pumps cannot exceed 85 % of the annual new installations.[10] The maximum rate of refurbishment increases from 1 % to 3 % during the period under consideration.

Industrial Process Heat: Moderate development. Due to technological innovations and the exploitation of efficiency potential (best available technology), industrial process heat demand is declining continuously by 0.5 % per year [19].

Based on these assumptions, three further scenarios are defined in which the influencing factors are each specifically changed.

8 By 2038 at the latest, no coal-fired power plants are to be on the grid in Germany. In 2032, it is to be reviewed whether the phase-out date can be brought forward to 2035 at the earliest in agreement with the operators. At the time of preparing the calculations for this study, no final decision had yet been made.

9 This assumption is a settlement. It is assumed that purely battery-electric drives will not cover the entire car population, as there will always be users who for various reasons decide to use other forms of drive (e.g. range, duration of charging, others).

10 This assumption is also a settlement. It is assumed that electric heat pumps will not cover the entire stock of heating systems, as there will always be users who for various reasons decide to use other heating technologies (e.g. temperature requirements in historical buildings, lack of availability of suitable heat sources, others).

2.3.2
Persistence Scenario

In this scenario it is assumed that the willingness of the population to switch to new technologies is very limited. This means a significant delay in the deployment of new technologies and an insistence on continuing to use today's conventional technologies, i.e. especially heating systems and vehicles with internal combustion engines. The main changes compared to the *Reference* scenario are the following:

Transport: Conservative development. Conventional internal combustion engines based on liquid fuels account for at least half of the annual new registrations in motorized private transport. There is no willingness in the population to flexibly control the batteries of electric cars in order to balance the electricity load.

Building Heat: Conservative development. Gas boilers account for at least half of new installations each year, while electric heat pumps are limited to 20 %. The rate of energy-related building refurbishments is constant at 1 %.

2.3.3
Non-Acceptance Scenario

Due to complex approval procedures and local resistance to the expansion of large infrastructures (i.e. transmission grids or wind turbines), their expansion may be significantly smaller than that corresponding to a cost-optimal development. In this scenario, a development is assumed in which larger infrastructure projects cannot contribute to the transformation of the energy system to the extent previously assumed. The most important changes compared to the *Reference* scenario are the following:

Energy Provision: The technical installation potential of onshore wind turbines is reduced to 80 GW_{el} [13]. A potential of 40 GW_{el} is assumed for offshore wind energy. To ensure that renewable energy sources continue to make a significant contribution to the electricity supply, the technical installation potential of photovoltaics is increased to 800 GW_{el} [12] (See comments about Table 1). The interconnection capacity for electricity imports will rise to only 20 GW_{el} by 2050, since here too it was assumed that the corresponding grid expansion would not be accepted.

Transport: For freight transport, there is no option to extend overhead lines on motorways. Only a small part of the total mileage in freight transport can be covered by battery electric vehicles.

2.3.4
Sufficiency Scenario

In this scenario, the influence of behavioral changes on a broad scale is examined. These changes are large enough to lead to a significant reduction in energy consumption. This beneficial effect could result, for example, from a strong change in values due to the increasing number of extreme events caused by climate change. The main changes in the *Sufficiency* scenario compared to the *Reference* scenario are based on the study commissioned by the Federal Environment Agency "Improving Climate Protection Modelling with *Sufficiency*" [20] and [21] and are summarized below:

Electricity Demand: It is assumed that the electricity demand for lighting, cooling, ICT and mechanical energy will decrease by 45 % compared to today's level.

Transport: Efficient development. Based on today's traffic volume, motorized private transport and air traffic are expected to decline by 30 % and 55 % respectively by 2050. Total mileage in freight transport will remain at today's level. In addition, end users are expected to be more willing to flexibly control their car batteries for load balancing.

Building Heat: Efficient development. The minimum rate of building energy retrofits increases from 1 % in 2020 to 2 % in 2050, while the maximum possible rate of energy refurbishment rises from 1 % to 3 % over the period under consideration.

Industrial process heat: Efficient development. The demand for industrial process heat will decline continuously by 0.75 % per year until 2050.

2.3.5 ***Reference100*** Scenario

The ***Reference100 scenario*** is based on the *Reference* scenario. However, a complete reduction of energy-related CO_2 emissions by 2050 is specified here as the boundary condition (i.e. minus 100 % relative to the 1990 value).

2.3.6 ***Sufficiency2035*** Scenario

The ***Sufficiency2035 scenario*** is based on the *Sufficiency* scenario. However, in this scenario it is assumed that a complete reduction in energy-related CO_2 emissions must be achieved as early as 2035.

3
Results

This chapter presents the results of the model calculations for the scenarios described above with a target of 95 % reduction in energy-related CO_2 emissions by 2050. First the energy provision is analyzed (Section 3.1) and then the individual consumption sectors of process heat, transport and building heating are discussed (Section 3.2). This is followed by a presentation of the results of the model calculations with a complete reduction of energy-related CO_2 emissions (Section 3.3) and finally a section dealing with cost aspects (Section 3.4).

3.1
Transformation of the Energy Supply

The aim of this chapter is to investigate the energy supply in the changing energy system. A presentation of the composition of primary energy and final energy in comparison to today's situation is followed by a more detailed analysis of the electricity generation, as electricity from renewable energy sources is becoming the most important primary energy.

3.1.1 Primary Energy and Final Energy

Germany's primary energy consumption in 2018 was 3641 TWh [5]. Excluding the non-energetic energy consumption of 247 TWh, 3394 TWh remain that are attributed to final energy applications and losses in the energy sector. The breakdown between the main energy sources (fossil, nuclear, biomass, electricity from variable renewable energy (VRE) and other renewable energy carriers) is shown in Figure 3 above. The final energy consumption was 2494 TWh and is also shown in the figure, divided into the main applications of low temperature heat (LT low temperature heat; space heating and hot water), heat for industrial processes (industrial PH), transport and the traditional applications of electricity (traditional electricity). The conversion efficiency is thus 73 %; 27 % are the losses in the energy sector. The largest share can be attributed to the conversion of fuels into electricity in conventional power plants.

In all of the four scenarios considered, primary energy consumption in 2050 is significantly lower than today, ranging from 52 % (Sufficiency) to 73 % (*Persistence*) of the current level. The reasons for the lower values are, on the one hand, the lower final energy de-mand and, on the other hand, the significantly reduced losses in the energy sector. The reduction in losses is due to the fact that only a very small proportion of electricity is generated in thermal power plants with corresponding losses. Depending on the scenario, the conversion efficiency is between 84 % and 92 %. Currently, the total renewable energy share in primary energy is around 15 %. In the four scenarios considered the share is consistently around 90 %, with variable renewable electricity, i.e. photovoltaics and wind energy, accounting for 50 % to 60 %.

The final energy of the four scenarios examined is between 60 % (*Sufficiency*) and 90 % (*Persistence*) of today's value. This reduction is due in particular to high efficiency on the use side of heat pumps and of electric drivetrains in road transport, and to lower space heating requirements due to energy-related refurbishment. Since all these measures have a much lower impact in the *Persistence* scenario, the reduction is noticeably smaller. In the *Sufficiency* scenario, the reduction in consumption due to behavioral changes has an additional mitigating effect, which explains the lowest value for final energy in 2050 in a comparison of the four scenarios.

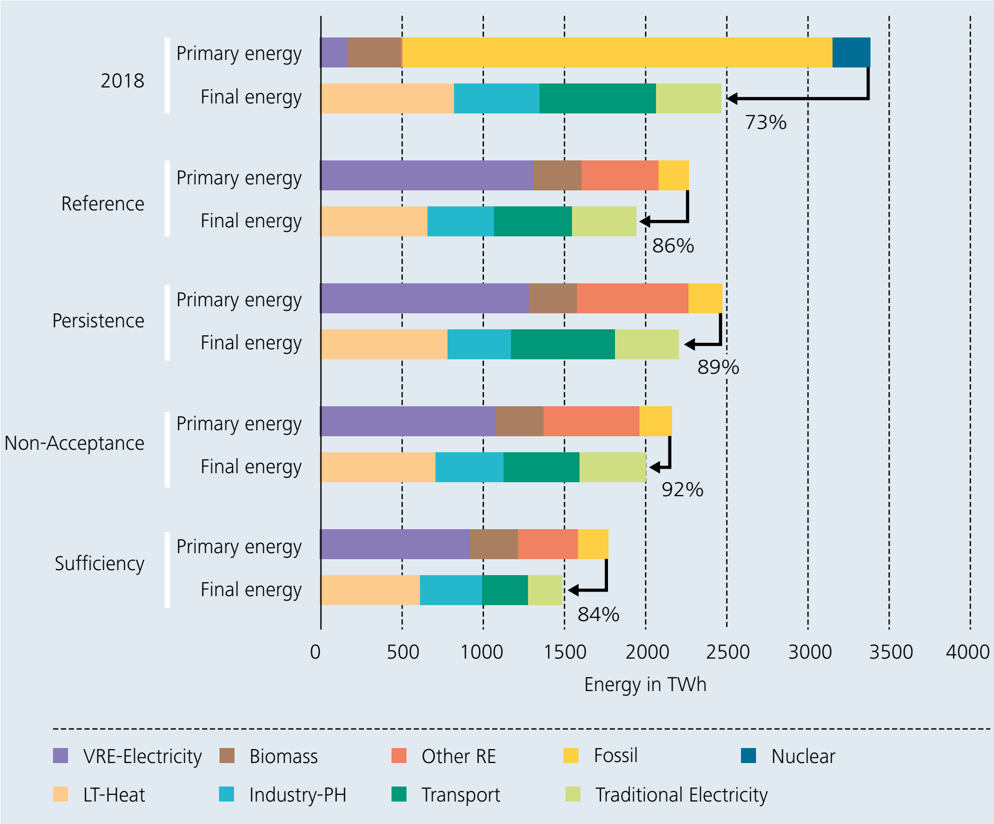


Figure 3: Primary energy mix subdivided into the primary energy sources, and the final energy subdivided into the main areas of application today for the four scenarios which lead to a reduction of 95 % energy-related CO_2 emissions by 2050 (VRE electricity: electricity from variable renewable energy sources (wind, sun); other RE: other renewables including geothermal, solar thermal and environmental heat; LT heat: low-temperature heat, i.e. space heating and hot water in the building sector; industrial PH: process heat in industry; trad. Electricity: traditional electricity applications such as lighting, ICT, refrigeration, stationary motors)

3.1.2 Development of Electricity Demand

The electricity sector currently accounts for around 40 % of energy-related CO_2 emissions in Germany [22]. In order to reduce the approximately 60 % of emissions from the areas of process heat, transport and building heat, a fundamental transformation away from fossil fuel use to renewables is necessary. As shown in the results in Figure 3, the greatest potential for renewable energy sources lies in wind energy and solar energy. Therefore a greater use of electricity for heating and transport is a sensible and necessary measure.

The decline of conventional fossil-fuel powered technologies in favor of electricity-based alternatives can be illustrated by the degree of electrification. This describes the proportion of energy demand in the individual sectors (traction energy in the transport sector or space heating in the building sector) that is covered by electricity-based technologies. This includes both the share of final energy used directly as electricity in the respective sectors as well as the share used indirectly via electricity-based fuels. A vehicle with an internal combustion engine thus increases the degree of electrification once it uses an electricity-based fuel. Compared to process heat, the degree of electrification in 2019 in road transport (less than 1 %) and in the supply of heat for buildings (4 %) is still very low. The reason for this is the high proportion of liquid burners and gas and oil boilers. Figure 4 shows the degree of electrification of the process heat, transport and space heating sectors for the years 2030 and 2050 in the scenarios examined.

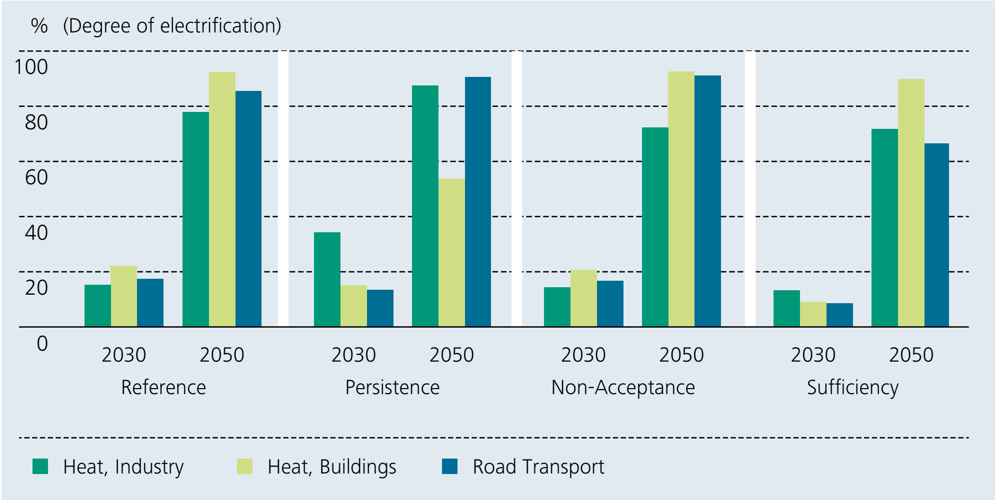


Figure 4: Development of the degree of electrification for the supply of process heat, space heating (including domestic hot water) and road transport. In addition to direct electricity use, the degree of electrification also takes into account the use of electricity-based fuels.

The results show that electrification of the sectors in the *Reference* scenario is implemented first for the supply of building heat (space heating and domestic hot water), followed by road transport and process heat. The high degree of electrification, including road transport and process heat provision, shows that the use of electricity will become increasingly important in these sectors by 2050. This change leads to a corresponding increase in electricity demand, which is summarized for the four scenarios in years 2030 and 2050 in Table 2.

Table 2: Annual electricity demand of the four scenarios analyzed in the years 2030 and 2050, including the electricity demand of Power-to-X technologies

Electricity Demand in TWh_{el}	Reference	Persistence	Non-Acceptance	Sufficiency
2030	683	718	656	546
2050	1447	1464	1282	1068

In 2030 the *Sufficiency* scenario shows the lowest electricity demand with 483 TWh_{el}, which is about 120 TWh_{el} less than demand in 2018 (597 TWh_{el}) [23]. This is due to two opposing effects: On the one hand, the increase in power-based technologies leads to an increase in electricity demand. On the other hand, total energy demand is significantly reduced by behavioral changes, including a reduction in distances travelled in road transport, in heated living spaces and in the consumption of industrial process heat. In all other scenarios, however, the demand for electricity increases continuously. In the *Sufficiency* scenario the electricity demand in 2050 is 1.7 times today's demand and in the *Persistence* scenario just under 2.5 times (See Table 2). This electricity demand includes both direct electricity and the indirect electricity needed for domestic hydrogen conversion and other synthetic energy carriers (Power-to-Gas, Power-to-Liquid). The indirect electricity use will account for about a quarter of the stated electricity demand in 2050.

3.1.3 Electricity Generation

An increase in electricity in the energy system only makes sense if electricity demand is met as emission-free as possible. An overview of the technologies in the electricity supply (in TWh_{el} per year) is shown in Figure 5 for the *Reference* scenario.

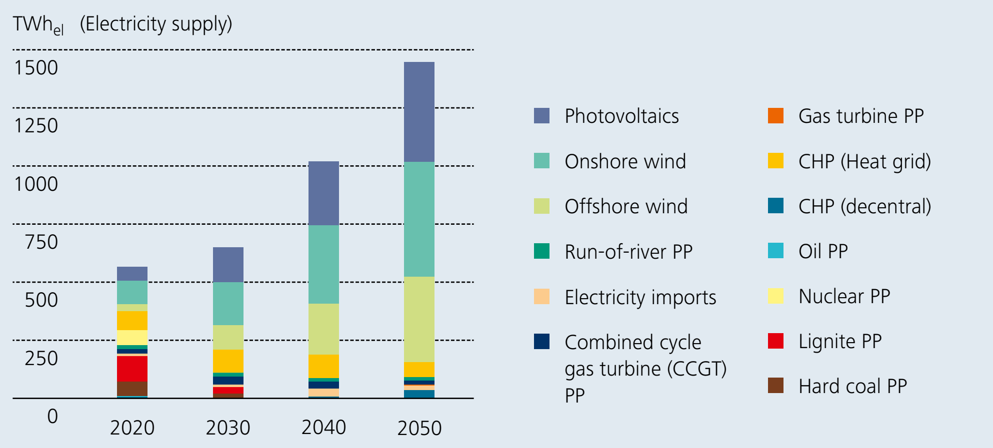


Figure 5: Development of the electricity supply by technology in the *Reference* scenario (PP = power plant)

Today, a large part of the total electricity demand, which is currently about 597 TWh_{el}, is met by nuclear power plants as well as lignite and hard coal-fired power plants. When the calculations were performed for this study, the decision has been made to phase-out nuclear power by 2022; however, the law to phase-out coal-fired power generation by 2038 at the latest had not yet been adopted [24]. The calculations assumed a more ambitious coal phase-out by 2035. There will be a slight increase in electricity imports from around 2030 onwards, in addition to the strong expansion of wind and solar power plants to replace the lost electricity. An additional compensatory effect has the electricity generation by decentralized CHP and fuel cells as well as large combined cycle gas plants (CCGT), which operate in combined heat and power generation and will contribute to the heat supply in heat grids from around 2030 onwards.

An overview of the share of renewable energy in electricity generation and the corresponding CO_2 factors for all four scenarios is shown in Table 3. The share of variable renewable energy sources in the electricity supply increases continuously over the period under consideration. In the *Reference* scenario, the renewable share rises from almost 40 % [25] in 2019, to 71 % in 2030 and to 93 % in 2050. One of the consequences of this transformation is that the CO_2 factor of electricity, which starts at 462 gCO_2/kWh_{el} in 2018 [26], drops to less than half at 147 gCO_2/kWh_{el} in 2030. The electricity generation is nearly without CO_2 emissions in 2050, with the CO_2 factor of electricity decreasing to 3 gCO_2/kWh_{el}.

Table 3: Composition of the electricity mix in 2030 and 2050 for the four scenarios analyzed (RES: Renewable Energy Systems).

	Reference		**Persistence**		**Non-Acceptance**		**Sufficiency**	
	Share RES %	CO_2 Factor g_{CO2}/kWh_{el}	Share RES %	CO_2 Factor g_{CO2}/kWh_{el}	Share RES %	CO_2 Factor g_{CO2}/kWh_{el}	Share RES %	CO_2 Factor g_{CO2}/kWh_{el}
2030	71	147	69	149	70	154	65	200
2050	93	3	93	5	92	7	92	9

In all of the scenarios, the CO_2 factor of electricity has similar values in the years 2030 with about 150 gCO_2/kWh_{el} and in 2050 with about 5 gCO_2/kWh_{el}. To meet the CO_2 reduction target, a renewable energy share of more than 70 % in the electricity mix is calculated for all scenarios in 2030 without assuming a decrease in consumption (*Sufficiency*). The share of renewable energy set by the German government is 65 % in 2030 [27]. The fact that this value is exceeded in all scenarios suggests that it will not be sufficient to achieve the targeted 55 % reduction in CO_2 emissions compared to 1990. Even in 2050, the target of an 80 % renewable energy share [27] in the electricity supply is clearly exceeded in all four scenarios; the average share is calculated to be 93 %. Electricity from wind and solar energy play a central role here.

Figure 6 shows the cumulative installed capacity for onshore and offshore wind turbines and photovoltaic systems, which are classified into east/west facing and south facing roof-mounted systems and south facing ground-mounted systems.

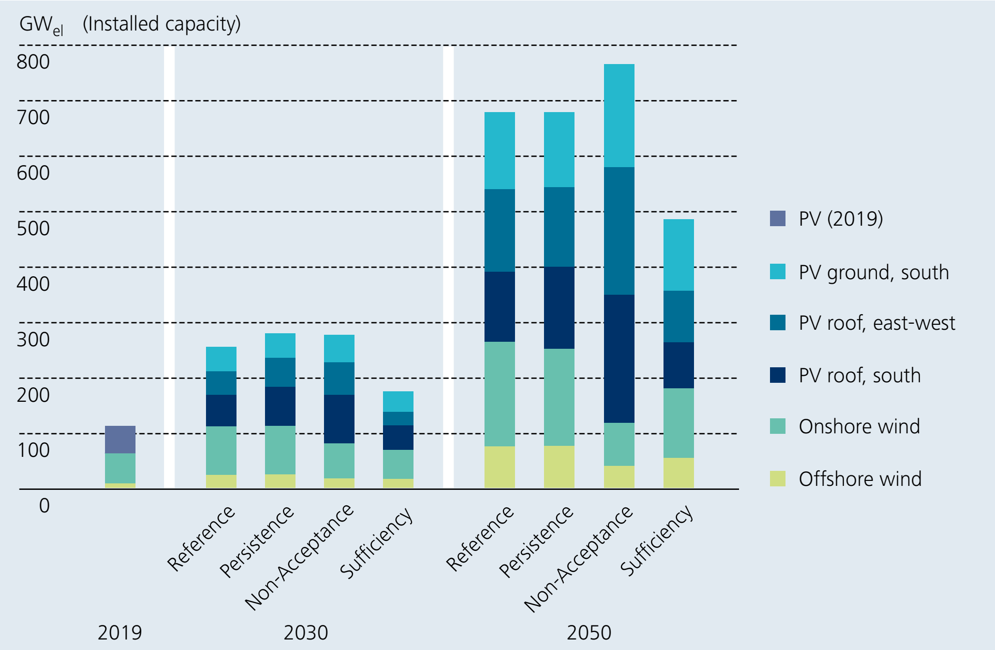


Figure 6: Cumulative installed capacity of photovoltaic systems and wind turbines in 2030 and 2050 for the four scenarios examined

Around 54 GW_{el} onshore and 8 GW_{el} offshore wind and 49 GW_{el} photovoltaic plants are installed in Germany in 2019 [25]. This amounts to a total capacity of 111 GW_{el} of variable renewable energy sources for electricity generation. The results of the scenarios show a doubling in the installed capacity by 2030 – with the exception of the *Sufficiency* scenario. In the *Reference* scenario, this means an average net increase in photovoltaic capacity of around 9 GW_{el} per year, as well as an annual increase of 3 GW_{el} for onshore wind and 1.5 GW_{el} for offshore wind, based on current values.

In the *Reference* and *Persistence* scenarios, the installed capacity of wind energy (onshore and offshore) increases to around 260 GW_{el} and that of photovoltaics to around 415 GW_{el} in 2050. This amounts to a total electricity generation of around 1300 TWh_{el} from photovoltaics and wind energy systems. In the *Sufficiency* scenario, the installed capacity is about 480 GW_{el}, or about 200 GW_{el} lower. This means that almost 30 % less electricity is provided by RES. Due to the lack of acceptance for changes in large infrastructures assumed in the *Non-Acceptance* scenario, about 140 GW_{el} less wind capacity is installed here, but therefore, an additional 230 GW_{el} photovoltaic capacity compared to the *Reference* scenario. As a result, the total installed capacity of RES is around 90 GW_{el} higher than in the *Reference* scenario. Since wind turbines have higher full-load hours than photovoltaic systems, around 230 TWh_{el} less electricity is provided from RES in the *Non-Acceptance* scenario than in the *Reference* scenario, despite an overall higher installed capacity. In addition, electricity generation from photovoltaic plants is characterized by a pronounced daily and seasonal pattern. This poses additional challenges to the *Non-Acceptance* scenario in order to guarantee a secure supply every hour of the year. Accordingly, systemic adjustments must be made to compensate for a limited expansion of wind energy. What effect this has on the system development with respect to storage and synthetically produced energy carriers will be described in detail in the following chapters

3.1.4 Balancing Variable Electricity Generation

Variable renewable energy sources (VRE) play a key role in the success of the energy transition and will become the mainstay of the energy supply in 2050. However, their further expansion requires that the variable electricity feed-in can be used sensibly in the energy system whenever possible. To achieve this, it is necessary to reconcile electricity demand and generation at all times. In order to meet the electricity demand when the feed-in from variable renewable energy sources or the discharge of short-term storage facilities such as batteries or pumped storage power plants is not sufficient, the operation of controllable power plants is also necessary in the long term. Their installed capacity is shown in Figure 7 for the years 2030 and 2050. To compare, the cumulative installed capacity of conventional power plants in Germany is currently around 85 GW_{el}.

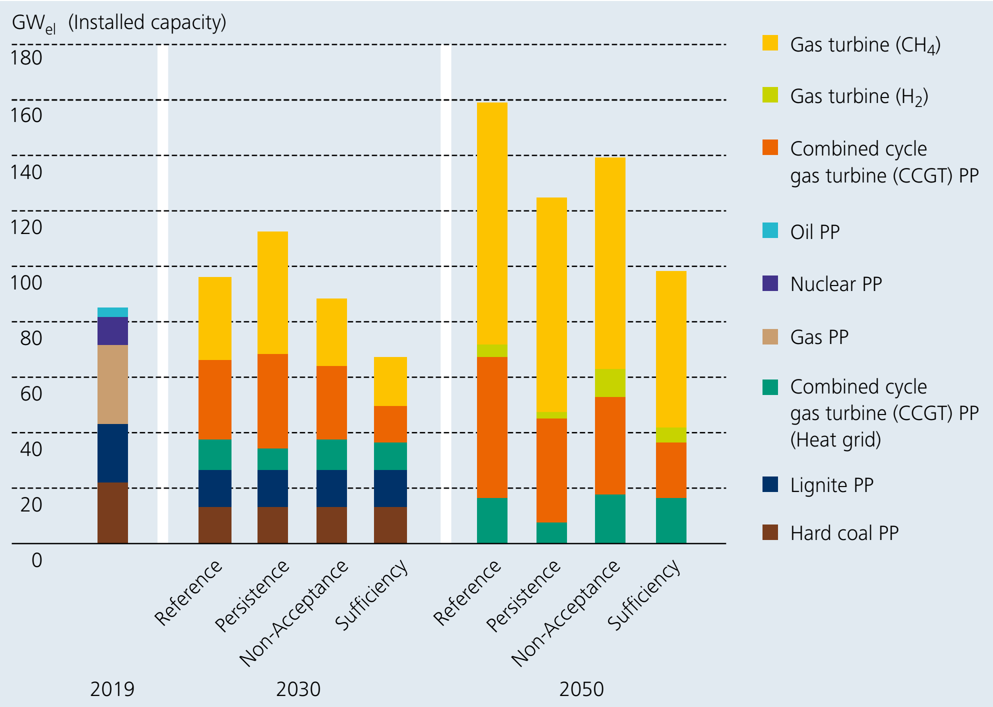


Figure 7: Cumulative installed capacity of conventional or controllable power plants in 2030 and 2050 in the four scenarios examined (PP: power plant)

In the *Reference* and *Persistence* scenarios, the installed capacity increases to 95 GW_{el} and 112 GW_{el} by 2030, respectively. On the other hand, the installed capacity in the *Non-Acceptance* scenario remains roughly at today's level. In this scenario, both the expansion of wind turbines and the electricity trade with neighboring countries are restricted. This combined with the earlier and greater expansion of both photovoltaic systems and electricity storage (see Figure 6 and Figure 8) leads to a reduction in the required capacity of controllable power plants. In the *Sufficiency* scenario, the assumed decline in electricity consumption throughout all sectors causes a slight decrease in the corresponding power plant capacity.

In addition to a decline in coal-fired power plants from 45 GW_{el} in 2018 to 25 GW_{el} in 2030 [25], a significant increase in highly flexible gas turbines is seen within all scenarios considered. Due to their comparatively short start-up times, these technologies are becoming increasingly relevant in a system that is largely characterized by variable renewable energy. This becomes more evident in 2050. Since coal-fired power plants no longer play a role at this time, the majority of controllable power plant output will be provided by combined cycle gas turbine CCGT power plants (with or without heat recovery) and gas turbine power plants. Overall, the cumulative generation capacity of controllable power plants in 2050 varies between 100 GW_{el} and 160 GW_{el}, depending on the scenario. A reserve capacity of 20 % was always used as a basis for dimensioning. The increasing share of variable renewable energy in the electricity supply and their prioritized feed-in to the grid have a significant influence on the operation of the controllable power plant park. Thus, their task is to increasingly cover peak loads instead of base loads, i.e. to provide power instead of energy. This means that the annual full-load hours of thermal power plants are continuously decreasing, a trend that can already be deduced from the development over the last few years [5].

Aside from thermal power plants to cover peak loads, electrical storage systems can be used to balance load and generation. In addition to the pumped storage power plants already in use today, stationary battery storage systems represent an important option. The development of the installed capacity of stationary battery storage is shown from 2020 to 2050 for the four scenarios in Figure 8.

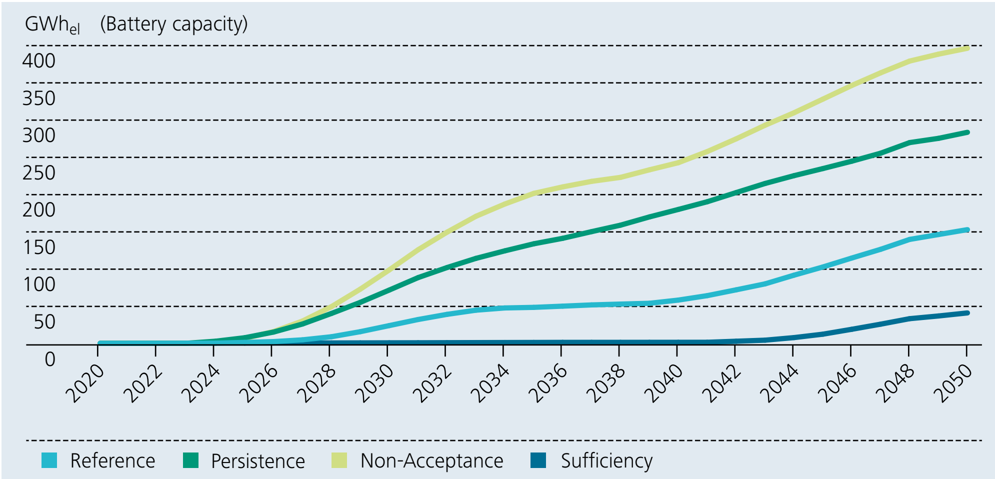


Figure 8:
Development of the installed capacity of stationary battery storage in the four scenarios examined

Short-term electricity storage plays an important role in all scenarios. While storage capacity reaches a value of around 150 GWh_{el} in the *Reference* scenario and around 50 GWh_{el} in the *Sufficiency* scenario by 2050, the installed capacity is significantly higher at 300 GWh_{el} for the *Persistence* scenario and 400 GWh_{el} for the *Non-Acceptance* scenario. This high value in the *Non-Acceptance* scenario is due to the fact that the ratio of installed wind power and solar power is not optimal and thus results in an imbalanced energy supply. The daytime peak of electricity generation by photovoltaics can be partially compensated by battery storage, achieving a shift to evening and night hours. In this scenario, a limited expansion of electricity transmission capacity to neighboring countries was also assumed. As a result, this reduces the possibility of importing electricity for load balancing. Here too, more storage capacity can improve the situation.

The comparatively high expansion of stationary battery storage in the *Persistence* scenario is also due to limited options for load balancing. In this scenario, for example, it was assumed that the use of vehicle storage units as flexible loads and generators, thus compensating for stationary battery storage, would not be accepted. In addition, the flexible operation of electricity-based heat generators in residential buildings, such as heat pumps in combination with thermal energy storage which enable excess electricity to be stored in the form of thermal energy, is not possible. In the *Sufficiency* scenario, on the other hand, battery storage facilities first become necessary towards the end of the considered period, and the required storage capacity in 2050 is calculated to be significantly lower than for the other scenarios. The reasons for this are a high level of acceptance for the flexibility options offered by vehicles and heat pumps in conjunction with a decline in the electricity consumption of traditional electricity applications which leads to a correspondingly lower expansion of wind turbines and photovoltaic installations.

Another option for balancing load and generation are electrolyzers, which can be used to produce electricity-based fuels such as hydrogen, methane or liquid fuels. Their integration into the energy system has several advantages:

- The energy carriers thus generated can be used in applications where a direct use of electricity is difficult to implement. Examples are liquid fuels for maritime and air traffic or hydrocarbons for the chemical industry.
- Suitable electrolyzers (e.g. PEM: Proton Exchange Membrane; AEL: alkaline electrolyzer) which allow rapid start-up and shut-down processes can be used as flexible loads, thus increasing the potential for integrating variable renewable electricity into the energy system.
- In times of high electricity feed-in from renewables, these processes can be used to produce electricity-based energy carriers which can be stored with almost no losses over a period of several days or months. These energy carriers can also be used in controllable power plants at times of low electricity feed-in from renewable energy sources, thus securing electricity generation in the long term without the use of fossil fuels.

The extent to which these technologies are installed in each of the considered scenarios is shown in Figure 9.

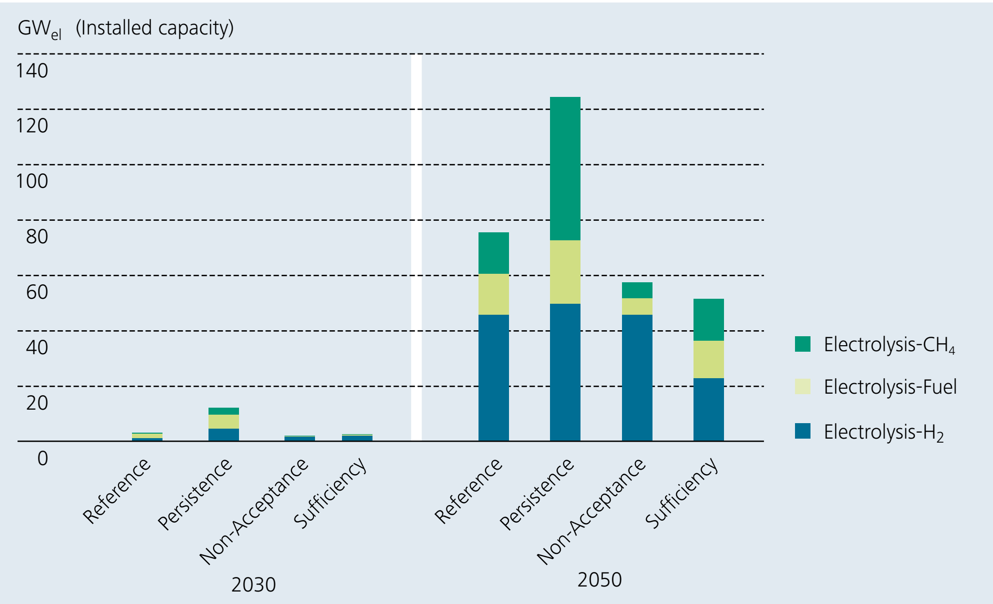


Figure 9: Cumulative installed electrolyzer capacity used for the generation of electricity-based energy carriers in 2030 and 2050 for the four scenarios examined (ElectrolysisCH_4: for the production of synthetic methane; ElectrolysisFuel: for the production of liquid synthetic energy carriers; ElectrolysisH_2: for the production of hydrogen, as final energy carrier.)

Although the synthetic production of energy carriers still plays a subordinate role in 2030, its importance is already apparent in the *Persistence* scenario with a contribution of 10 GW_{el}. In 2050 its generation capacity rises to over 120 GW_{el}. The combustion technologies assumed in this scenario for road transport and for the building heat supply are equivalent to today's use. These require replacement by renewable synthetic energy carriers.

In the other scenarios, the total installed capacity of electrolyzers in 2050 is between 50 GW_{el} and 75 GW_{el}. Even with strong behavioral changes and the resulting reductions in consumption as assumed in the *Sufficiency* scenario, and despite the possibility of importing renewable synthetic energy carriers from abroad (see Section 3.1.5 below), a domestic hydrogen economy is shown to be a meaningful part of a fossil-free, renewable-based energy system.

One argument repeatedly put forward against renewable energy sources is that they do not provide a base load. Today, however, we are witnessing a fundamental paradigm shift in energy supply. The demand-based energy supply by large power plants, which was predominant in the past, is increasingly being replaced by a system in which there is a continuous balance between energy supply based on renewable sources, which are conditionally controllable and predictable, and the most flexible energy use possible. This results in a complex interplay between energy supply and time-adjusted energy use (load shifting, demand response), which includes a stronger coupling of the electricity, heat and transport sectors, the temporary use of flexible generators and storage facilities of various designs. As an example, Figure 10 shows the profile of electricity generation and consumption for one week in April 2050 as calculated in the *Reference* scenario. The graph shows how the integration of photovoltaics and wind energy in a future energy system may perform on an hourly basis.

In the lower graph, the residual load, defined as the difference between non-controllable power generation, essentially wind energy and photovoltaics, and the non-shiftable base load (e.g. industrial processes) is shown. Positive residual load means that the current power is not sufficient due to non-controllable energy generation. Negative residual load means that there is electricity available which can be used by switchable loads or to charge storage devices. When photovoltaic feed-in peaks during midday (yellow), short-term storage devices are charged accordingly (red, stationary batteries) and then electricity is converted into synthetic energy carriers or, if possible, into flexible heat generators, e.g. to charge heat storage. This operation can be seen, for example, in hours 12 and 36. From hour 50 onwards, the residual load is negative over a longer period of time due to the high electricity input from wind power. The electrolyzer plants operate more continuously than on the previous days, when operation was only during daytime. The generated hydrogen and any synthetic energy carriers produced from it, such as methane or liquid energy carriers, can be stored for longer periods of time and used as required. The addition of hydrogen-electric technologies (hydrogen-electric vehicles, fuel cells or boilers to provide space or process heat) reduces the direct demand for electricity. Another option for using peaks in electricity generation is to raise the temperature level of thermal energy storage (hot water storage) by converting electrical energy into thermal energy with heating rods (hour 160). If all of the thermal energy storage systems are full, then the excess electricity is exported. As a last option, systems are shutdown (hour 156 and following). If the electricity feed-in from renewable energy sources is not sufficient, such as in windless nights, the electricity demand is covered by discharging short-term storage tanks (hours 20, 45, red), importing electricity (hour 24, purple) or operating thermal power plants (hour 27, CCGT, light green).

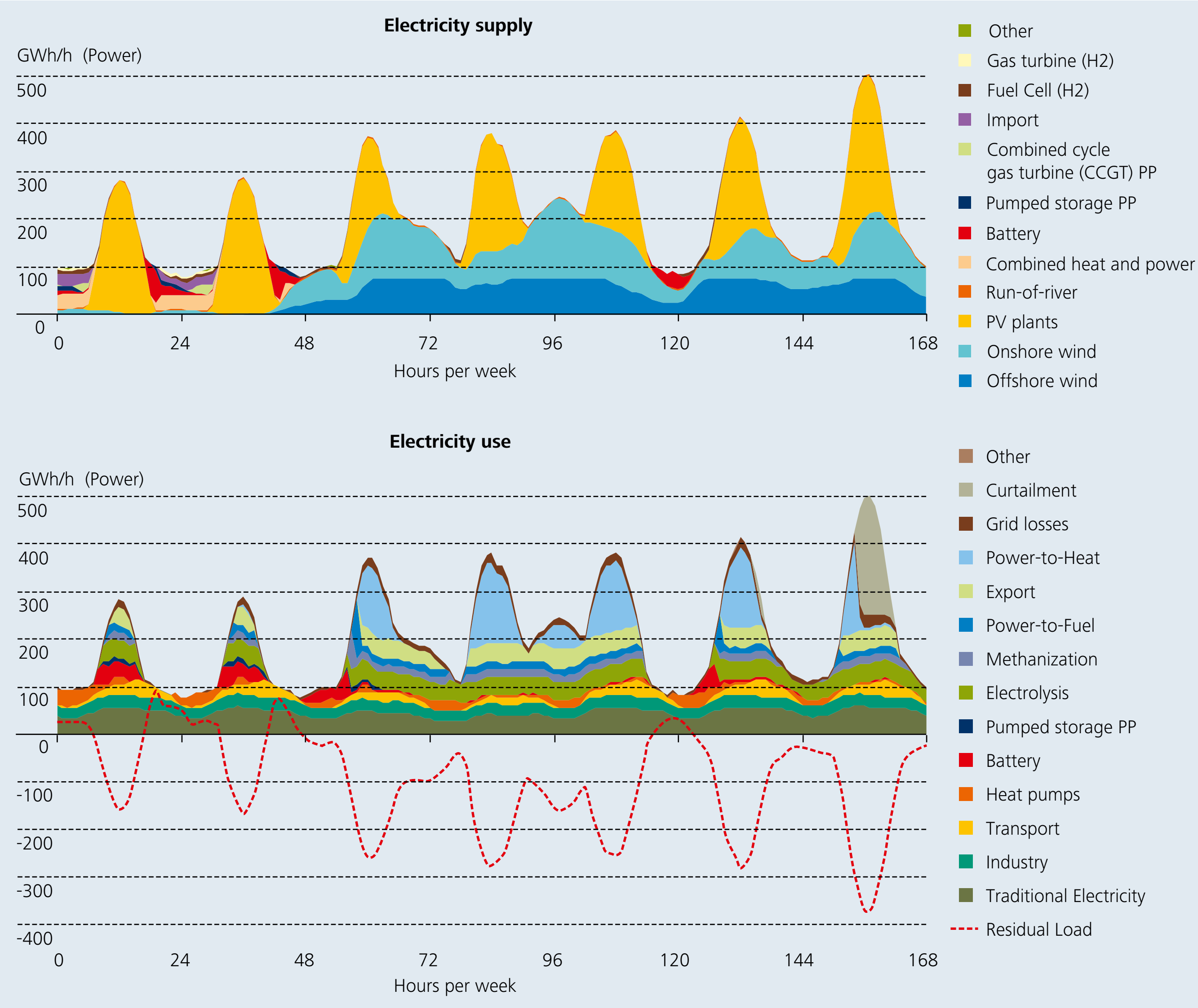


Figure 10: Exemplary profile showing electricity supply and demand in April 2050 for the Reference scenario. The residual load is the difference between the hourly electricity generated by wind and photovoltaics and the non-shiftable base load in the power grid.

In order to guarantee a secure supply even at times when variable renewable energy power plants provide insufficient electricity over several consecutive days, it is necessary to operate controllable power plants. Figure 11 shows the electricity generation and consumption for one week in October 2050 as calculated in the *Reference* scenario. While the peak power reached almost 500 GW_{el} in exemplary April week shown in Figure 10, the maximum generation from wind and solar in the week shown here is only 180 GW_{el}.

In the first 40 hours of the week shown, the electrical load is balanced mostly by electricity generated by wind and photovoltaics. The residual load is close to zero. In addition, combined heat and power plants and hydrogen-based fuel cells simultaneously generate electrical energy when covering the heating load. Around hours 13 and 24 there is a slight excess of electricity, so that electric batteries can be charged (red) and electricity can be converted into heat (light blue).

As a result of a decline in the feed-in from photovoltaic and wind, electricity generation is no longer sufficient to cover the electrical load from hour 40 onwards, and the residual load becomes positive. To balance the residual load, stationary batteries are first discharged (red). Due to the steady decrease in the electricity from wind, the electrical load can be covered by photovoltaic systems only during the feed-in peaks in the hours from 50 to 60. Once the photovoltaic feed-in wanes, then other power plants come into play to perform a balancing function and cover the current load. Pumped storage power plants (dark blue) and gas turbine

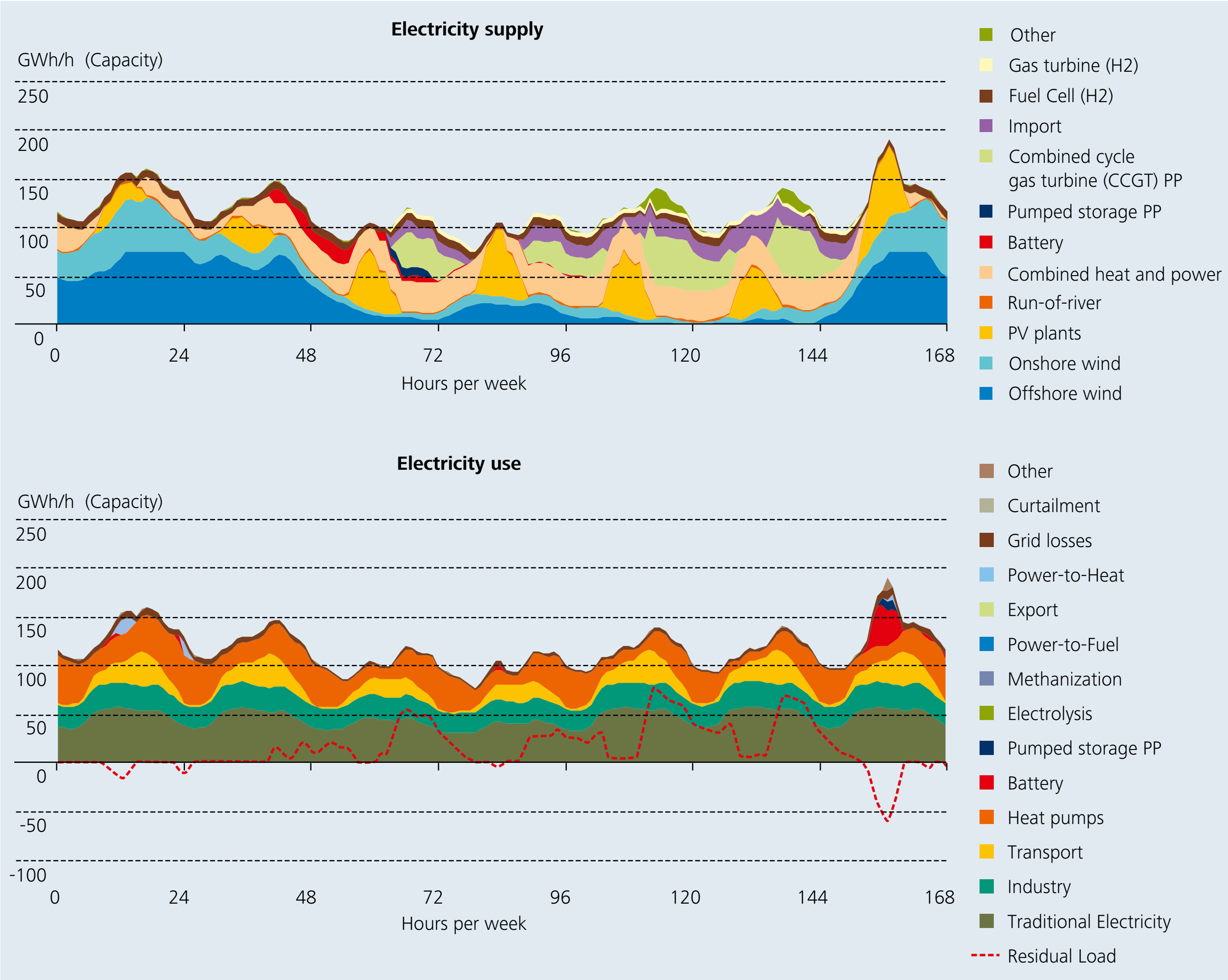


Figure 11: Exemplary profile for electricity supply and demand in October 2050 for the Reference scenario

combined cycle power plants (CCPP) (light green) are used here. During this period, electricity is also imported from Germany's neighboring countries (violet). This condition persists up to hour 150, in which the feed-in from wind and solar increases again and from hour 153 onwards leads to a negative residual load. Now the stationary batteries (red) and pumped storage power plants (dark blue) are being recharged.

The time series shown underline the significantly changed operation of controllable power plants in the future compared to today. While the flexibility requirements for these power plants increase, the full-load hours – and thus the fuel consumption – decrease.

3.1.5 Fossil and Synthetic Energy Carriers

In addition to the domestic production of synthetic energy carriers by electrolysis, the option of importing these energy carriers from abroad is taken into account in all of the models. The price development for these energy carriers was taken from a study carried out for the Federal Ministry of Transport and Digital Infrastructure (BMVI) [15] [11].

11 The underlying prices were estimated for a production in North Africa and include not only plant costs but also costs for the capture of carbon from the air (if necessary) and the transport of the respective energy carriers to Germany by tankers (including compression and liquefaction, if necessary). Other transaction costs or costs that could result from the political (domestic) stability of the exporting countries were not considered in this study. Data on the cost development for the respective energy carriers can be found in the appendix of the study, which is available on the Internet.

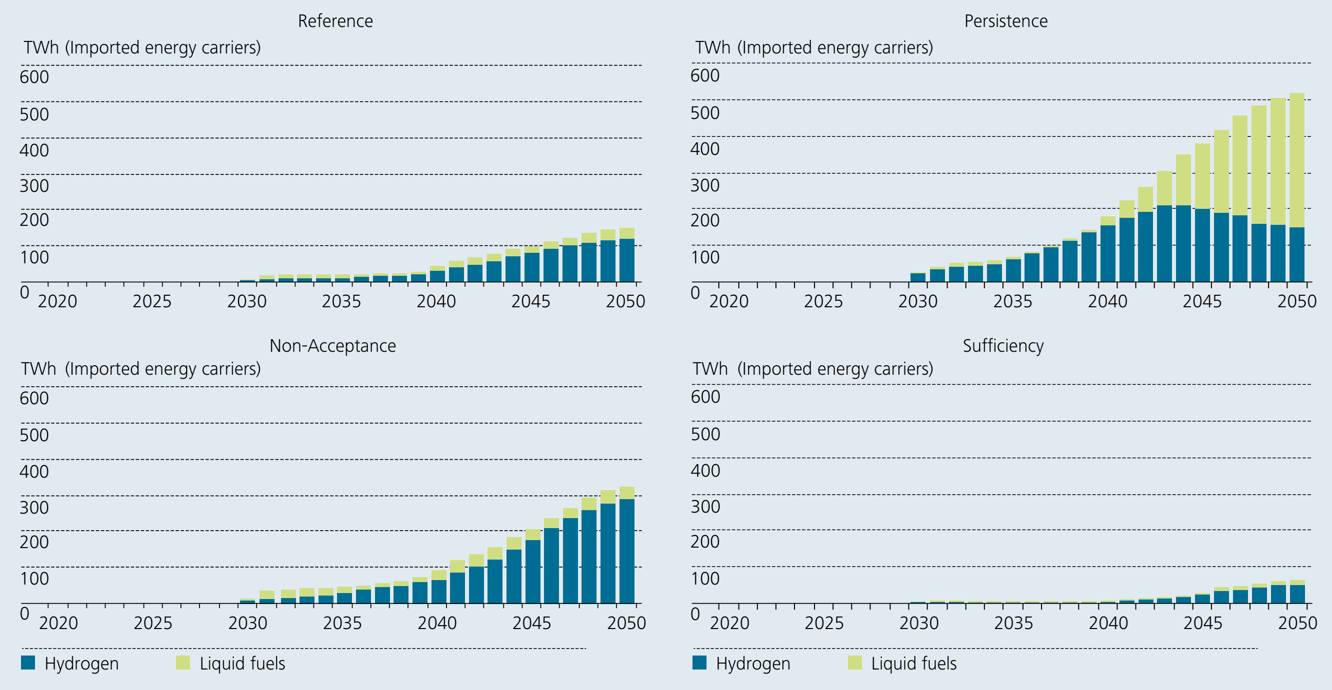


Figure 12:
The course of the imported synthetic energy carriers produced abroad by electrolysis and converted to hydrogen with renewables from 2020 to 2050 for the four scenarios examined

The possibility of importing synthetic energy carriers is used in all scenarios, although the respective quantities vary greatly. The import of synthetic energy carriers does not completely replace domestic production, but rather it represents an additional measure. It therefore makes sense to not only produce synthetic energy carriers domestically from renewable energy sources but also to import them from abroad. The lower full-load operational hours of the domestic plants are more than compensated by the systemic benefits described in the previous section. The benefit of domestic electrolyzer plants not only lies in the provision of CO_2-neutral energy carriers, but also in the ability to make use of domestic renewable electricity to a greater extent (see Figure 9.)

In the *Reference* scenario, the amount of imported hydrogen and synthetic liquid fuels reaches a maximum of 150 TWh per year. In the *Sufficiency* scenario imports reach only half at around 75 TWh. In the scenarios *Non-Acceptance* and *Persistence*, on the other hand, the imported quantities are significantly higher at more than 300 TWh and 500 TWh respectively. Despite the varying import volumes in the different scenarios, the import of synthetic fuels should be considered in relation to the decline in fossil fuel use. As an example for the *Reference* scenario, Figure 13 shows the quantity of fossil fuels used for the period from 2020 to 2050.

In 2018, around 2700 TWh of fossil fuels were used in Germany [28]. The majority of these are natural gas, mineral oil, hard coal and lignite. Due to the lack of domestic resources and the phasing out of hard coal mining, these energy sources are almost exclusively imported from abroad [29]. In order to achieve the targets for the reduction of energy-related CO_2 emissions, fossil fuel imports decrease continuously and reach a value of almost 200 TWh in 2050 in the *Reference* scenario, which corresponds to about 7 % of the quantity imported today. This shows that restructuring the energy system, in addition to meeting the climate targets, will also significantly reduce Germany's dependence on energy from other countries.

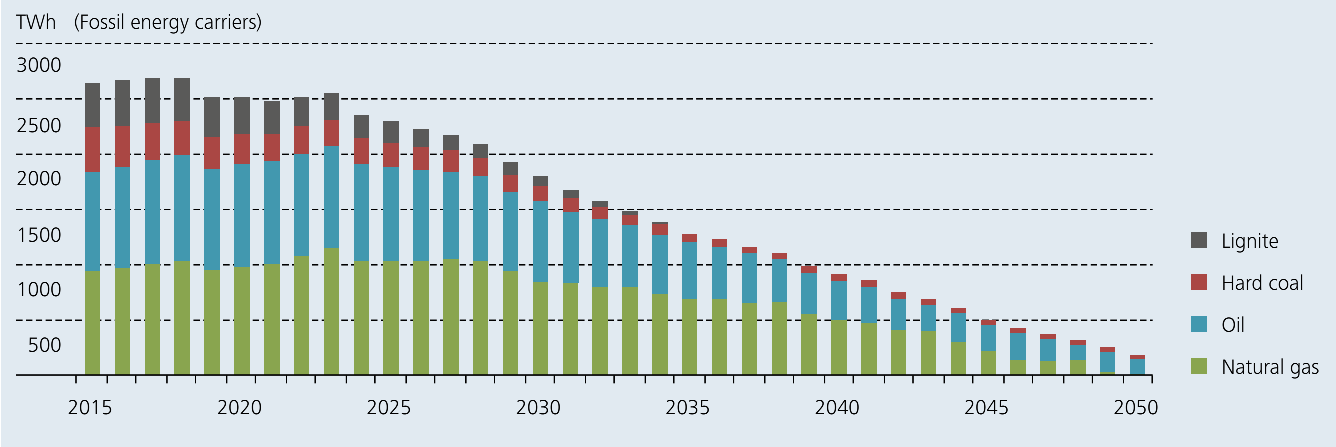
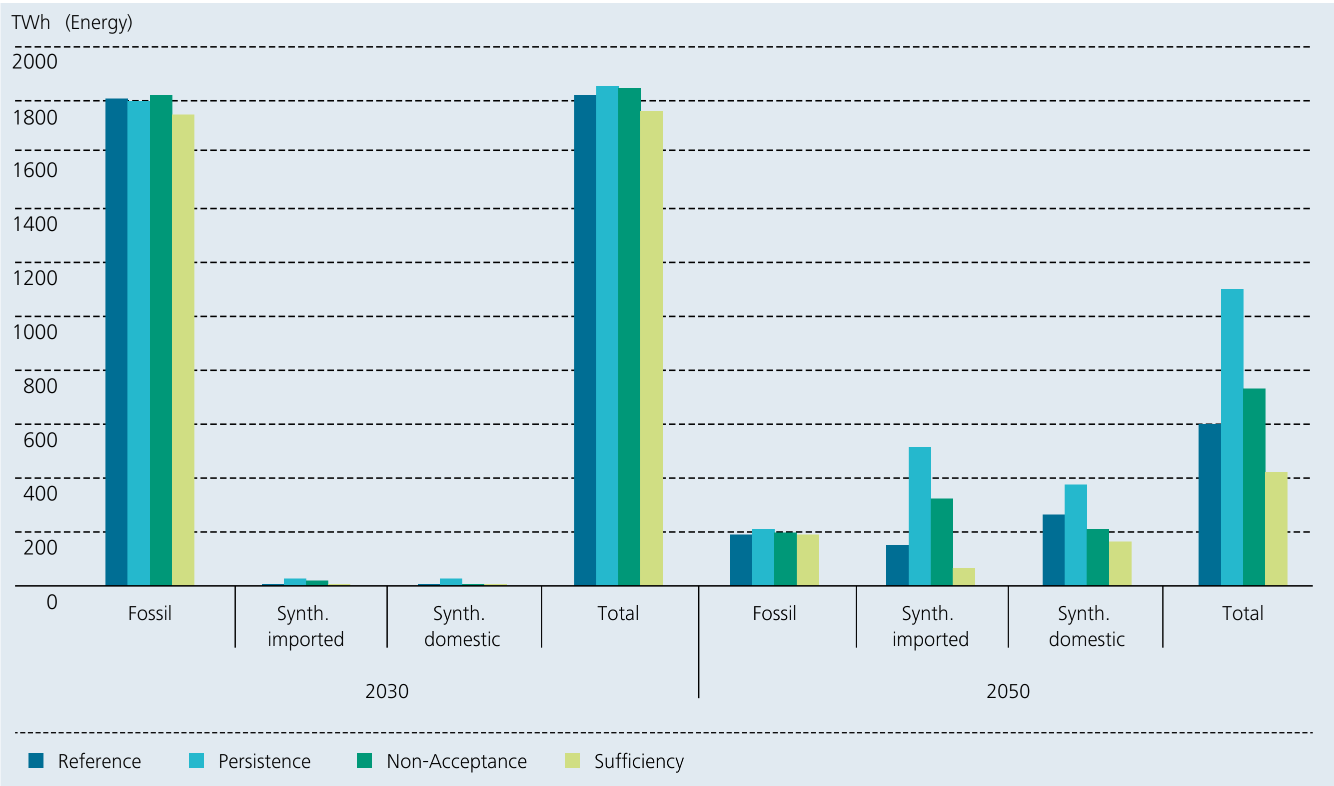


Figure 13:
Fossil fuel use from 2015 to 2050 for the Reference scenario. The majority is imported.

Figure 14 shows the total quantity and origin of material energy carriers for the years 2030 and 2050 in the four scenarios.

In 2030 the share of fossil fuels will predominate in all four scenarios. The share of synthetic energy carriers produced using renewable electricity – whether abroad or domestically – is still very small. In 2050, on the other hand, the differences are much greater for the four scenarios, both in terms of total quantity and origin. In all scenarios, the share of fossil fuels is very similar with a value of around 200 TWh, which is largely determined by the specified CO_2 emissions set as a fixed boundary condition in the simulations. In contrast, the quantities of synthetically produced energy sources (domestic and imports) range from around 230 TWh in the *Sufficiency* scenario to almost 890 TWh in the *Persistence* scenario. The high value in the latter is due to the high stock of internal combustion technologies for the supply of heat and for transport, which are still being used in 2050 in this scenario.

Figure 14:
Composition of material energy carriers and their origin for the four scenarios in the years 2030 and 2050.



3.2
Sector-specific Analysis

In this chapter, the consumption sectors of process heat, transport and building heat are analyzed in more detail for the four scenarios examined.

3.2.1 Industrial Process Heat

In 2018, the supply of process heat accounted for 565 TWh_{th}, which corresponds to around 30 % of Germany's final energy demand. Accounting for around 90 % of consumption, industry plays a central role here [5]. Depending on the industry and the processes used, the required temperature level varies from 100 °C and below to processes requiring several thousand degrees Celsius [19]. Due to this wide variation, different technologies are possible for the supply of process heat, depending on the given temperature range. For the calculations and the evaluation of results, the process heat requirement was divided into three segments. The **low-temperature segment** extends up to 100 °C and includes processes such as bleaching, dying and washing in the textile industry as well as pasteurization, blanching, scalding, cooking and smoking in the food industry. The **medium temperature segment** covers the range from 100 °C to 500 °C. Typical processes in this temperature range are distillation in the chemical industry, pressing in the woodworking industry, baking in the food industry and drying processes across all industries. The **high-temperature segment** includes all industrial processes with temperature levels above 500 °C. Particularly energy-intensive in this segment - in ascending order - are the chemical industry, the processing of glass, ceramics, stone and earth, and metal production and processing.

Figure 15 shows the energy sources used for the process heat supply for the low temperature segment for the years 2030 and 2050 in each of the four scenarios.

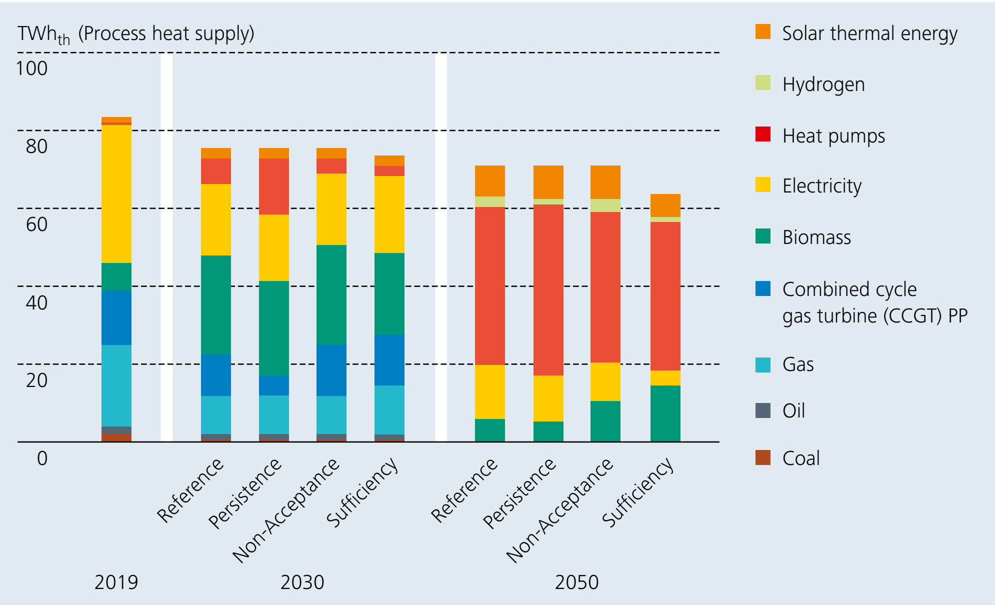


Figure 15: Process heat supply according to technology options in the low temperature segment (up to 100 °C) in 2030 and 2050 for the four scenarios examined

The **low-temperature segment** is responsible for around 18 % of the total process heat demand in Germany [3], and in 2018 the final energy demand was 102 TWh_{th}. This corresponds to a useful heat demand of about 81 TWh_{th}. It is assumed that this will be 75 TWh_{th} in 2030 and will fall to around 70 TWh_{th} by 2050. This reduction is based on the assumption that annual efficiency gains averaging 0.5 % can be achieved by using the best available technology (BAT). In the *Sufficiency* scenario, a slight decline in consumption and thus production is also assumed, which reduces the demand for process heat by an additional 0.25 % per year.

Despite the different assumptions in each scenario, a similar trend can be observed in the generation technologies used for the supply of process heat. While a wide variety of technologies will still be used for the supply of heat in 2030, technologies with lower CO_2 emissions will begin to replace combustion-based technologies from 2030 to 2050. Thus in 2050, solar thermal, heat pumps, electrode and hydrogen boilers will be used almost exclusively, with heat pumps accounting for the largest share (see Figure 15).

From 2030 onwards, the share of heat pumps will increase sharply, reaching almost 60 % in the low-temperature segment in 2050. One reason for this development is their average coefficient of performance of 2.5, which results in lower final energy consumption (as compared to a conventional boiler). This factor is becoming increasingly important as emissions reduction targets become more ambitious. Besides heat pumps, other electricity or hydrogen-based technologies provide low-temperature process heat. Both options benefit indirectly from an increase in renewable electricity in the system and the associated reduction of the CO_2 factor of electricity (see Table 3). Renewable heat is also provided by solar thermal systems. Their contribution increases continuously over time with the scenario average reaching around 11 % in 2050.

Consumption in the **medium temperature segment** (100 - 500 °C) currently accounts for 18 % of total process heat demand. The technologies for heat supply in 2030 and 2050 for the four scenarios are shown in Figure 16.

In this temperature segment, too, a displacement of conventional, fuel-based technologies is evident in the period up to 2050. Instead of oil and gas boilers, variants with lower CO_2 emissions are increasingly being used, such as the combustion of biomass. This result represents a significant difference to heat supply in the sector of space heating and domestic hot water, where biomass will hardly be used in 2050. At the same time, the use of electricity to provide process heat via heating elements is increasing. This change concerns, for example, the provision of steam and hot water. Today fuel-based heat generators are generally

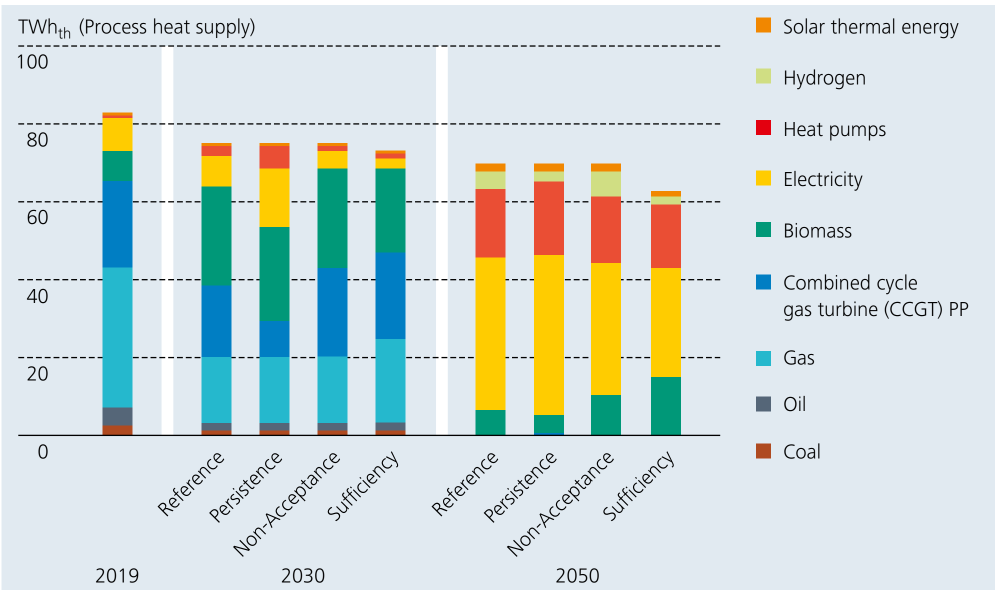


Figure 16:
Process heat supply by technology in the medium temperature segment (100 - 500 °C) in 2030 and 2050 for the four scenarios examined

used for this purpose, yet there is great potential for electrification. Figure 16 shows the increase in indirect and direct electricity use, particularly through the use of hydrogen, electrode boilers and heat pumps. In the case of heat pumps for use in industry, it has been assumed that by 2030 these will be able to provide process heat up to 180 °C, and by 2050 process heat up to 300 °C [30, 31]. These assumptions are based on the developments in suitable refrigeration circuits.

The third temperature segment describes processes above 500 °C and at 64 % accounts for the highest proportion of the total process heat requirement [3]. The technology for the heat supply in this segment is shown in Figure 17.

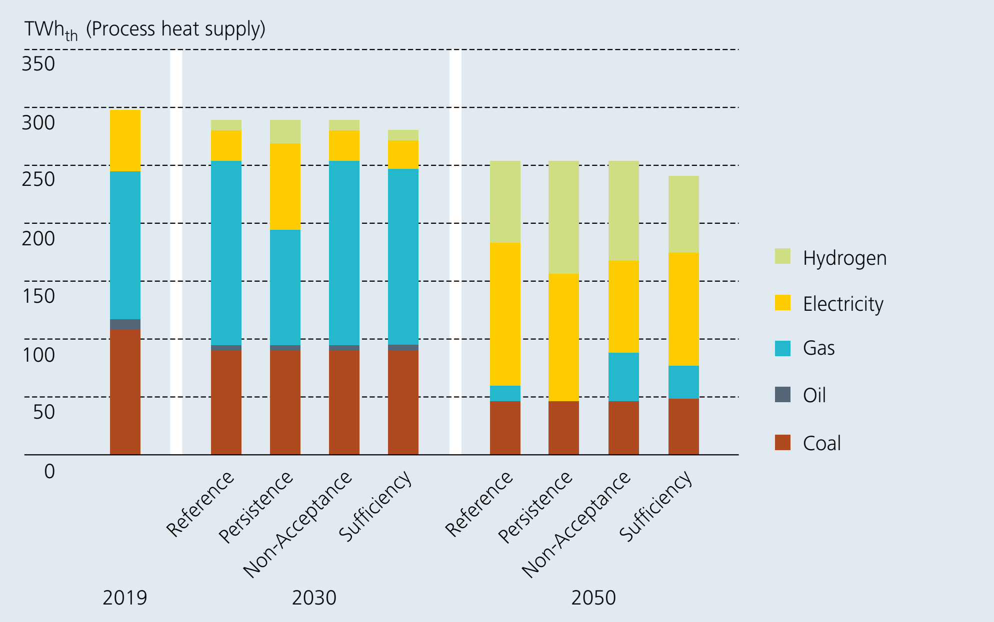


Figure 17:
Process heat supply by technology in the high-temperature segment (above 500 °C)

Due to the higher temperature requirements, only fuel-powered boilers can be used in the high-temperature segment. Heat pumps, solar thermal systems, biomass boilers and waste heat from combined heat and power generation therefore play no role in this segment. Accordingly, there will still be a high proportion of gas-fired boilers in 2030 in particular, although these will be largely replaced by hydrogen boilers and electric furnaces in 2050. At the same time, coal-fired boilers will decline over time. These will be mainly used for the production of crude steel. The steel production process is represented in the model by the primary and secondary route. In the primary, or blast furnace route, iron ore is reduced using coking coal to produce high-quality steel. The coal requirement for this process is assumed to be around 90 TWh (around 30 million t CO_2) in 2030 and about half of this in 2050 (around 15 million t CO_2). In the secondary route, steel is produced from steel scrap using electric arc furnaces. It is assumed that by 2050 steel produced in this manner will replace one third of the primary steel. The reason for this limitation is, on the one hand, the availability of steel scrap and, on the other hand, the fact that certain steel grades cannot be produced in this process. A further third of the carbon-intensive primary steel production process will be substituted by the increasing use of hydrogen [32].

Across all three temperature segments, a shift from conventional technologies to electricity-based technologies in the process heat sector is emerging in the form of direct use (heat pumps and electric boilers) or indirect use (hydrogen and methane-based processes). Electrically-based process heat technologies offer further advantages in addition to making use of renewable electricity. These include the fact that it is comparatively easy to guarantee high temperature levels and to achieve precise local and temporal heating, thus reducing losses. At the local level, these technologies also offer the advantage of no noise pollution and emissions.

3.2.2 Transport

With a final energy demand of 768 TWh in 2017 [33], the transport sector in Germany emitted about 168 million t CO_2 [34]. The model calculations assume that the energy demand of inland waterway, air and fuel-based railway transport will continue to be covered by liquid fuels due to their higher energy density. The reduction of CO_2 emissions in these application areas is therefore achieved by using an increasing proportion of CO_2-neutral liquid fuels such as biodiesel or synthetic energy carriers. In road transport, a "fuel switch" is possible by selecting different drivetrain technologies in the model. Motorized individual transport and road-bound freight transport are each represented by seven different drivetrain concepts. This makes it possible in the course of the optimization process to analyze both the continuation of using conventional as well as the change towards alternative drivetrain technologies.

Motorized Private Transport

In order to transform motorized private transport, the German government set the goal of increasing the number of electric vehicles on Germany's roads to up to 10 million vehicles by 2030 [27]. According to data from the Federal Motor Transport Authority, around one percent of all new vehicle registrations were electric vehicles in 2018 [35]. To achieve the target of 7 to 10 million electric vehicles in 2030, this share would have to increase to an average of 23 % to 33 % of all new registrations over the next ten years [12]. The results of the model show that the German federal government's targets are exceeded in all scenarios except the *Sufficiency* scenario. The number of vehicles per powertrain technology resulting from the calculations is shown in Figure 18 for the years 2030 and 2050 for the four scenarios examined.

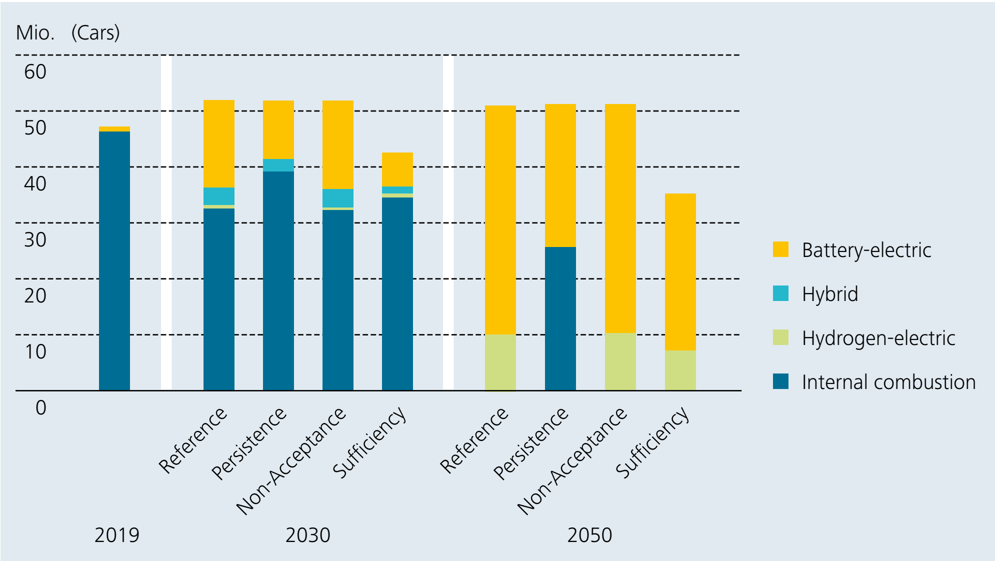


Figure 18: Powertrain technologies used in the passenger car sector in 2030 and 2050 for the four scenarios examined

12 Extrapolation assuming an average of 3.4 million new registrations per year

Today almost the entire fleet of around 47 million motorized private vehicles is based on internal combustion engines that run on predominantly on fossil fuels. In the *Reference* scenario the number of combustion-based vehicles in 2030 will be significantly smaller at 33 million vehicles. This decline is mainly compensated by battery electric vehicles, of which about 15 million will be in operation in 2030. In addition, there are another approx. 3 million hybrid vehicles and 540,000 hydrogen-electric vehicles. These figures correspond to an annual average of new registrations for the period from 2020 to 2030 of about 1.5 million battery electric vehicles, 300.000 hybrid vehicles and 50.000 hydrogen electric vehicles. With currently about 3.4 million new registrations per year [36], new registrations of battery electric vehicles would thus average around 44 % of new vehicles over the next 10 years. The model results indicate that the German federal government's target of 7 - 10 million battery electric vehicles in 2030 will probably not be sufficient to achieve the climate protection targets in a cost-optimized manner. The number of battery electric vehicles will rise to 40 million by 2050. According to the assumptions in the *Reference*, *Persistence* and *Non-Acceptance* scenarios, the share of battery electric vehicles can be maximum 80 % of the vehicle fleet (see footnote in Section 2.3), and therefore the remaining share in the *Reference* scenario in 2050 is based on hydrogen-electric vehicles. This means that a 95 % reduction in CO_2 emissions compared to 1990 would cause a complete displacement of internal combustion engines in motorized private transport.

The trend shown in the *Reference* scenario in 2030 is essentially confirmed in the *Non-Acceptance* scenario. In the *Persistence* scenario, the share of battery electric vehicles is slightly lower in 2030 and noticeably lower in 2050 due to the assumption that at least 50 % of new registrations are combustion-based vehicles. At the same time, many vehicles with internal combustion engines will still be in operation in 2050, yet they will be predominantly powered by CO_2-neutral fuels (see Table 4). As explained in Chapter 3.1.4, the installed capacity of Power-to-Fuel plants and the amount of synthetic fuel imports required to provide these fuels are by far the largest in the *Persistence* scenario. In the *Sufficiency* scenario, on the other hand, the assumed decline in consumption (reduction in the number of vehicles and kilometers driven) means that in 2030 it will not yet be necessary to convert the motorized individual transport to the same extent as in the other scenarios in order to achieve the CO_2 reduction targets. Accordingly, the switch to battery-electric and hydrogen-electric powertrains will take place at a later date in the *Sufficiency* scenario.

In the *Reference*, *Sufficiency* and *Non-Acceptance* scenarios, electric-based powertrain concepts play a major role in the transformation of the energy system. Battery-electric and hydrogen-electric powertrains not only have higher efficiencies compared to combustion engines, but they also offer the potential for flexibility in the energy system. In battery electric vehicles, this is achieved by charging (grid-to-vehicle) or discharging (vehicle-to-grid) the vehicle battery as required by the energy system. Hydrogen-electric vehicles open up the possibility of shifting energy quantities over longer periods of time, even seasonally. For example, excess renewable electricity can be used for the production of hydrogen in summer and consumed in the winter months.

Road-bound Freight Transport

Analogous to motorized private transport, the distribution of powertrain technologies in road-bound freight transport is optimized for all four scenarios. The *Sufficiency* scenario assumes a 21 % decline in mileage, or tonne-kilometers driven, in 2050, based on today's figures (see Chapter 2.3).

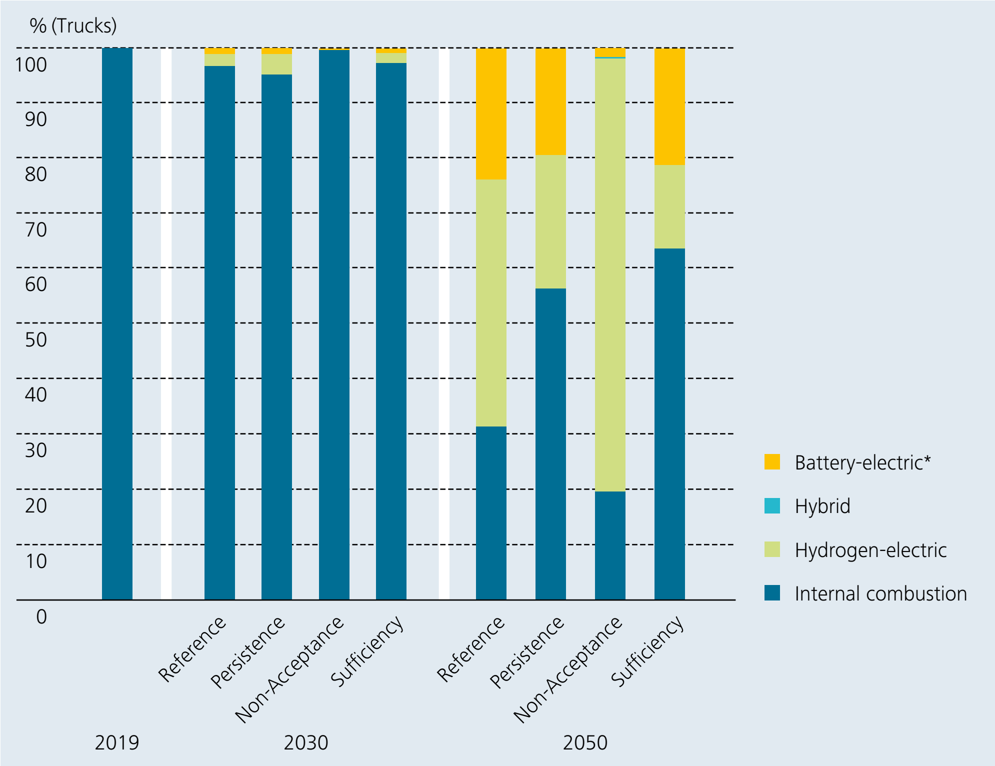


Figure 19:
Proportion of drive concepts (normalized to mileage) in the truck sector for the four scenarios examined in 2030 and 2050.

* purely battery-electric powertrains including overhead-line trucks, with the exception of the Non-Acceptance scenario in which no overhead-line trucks are considered

Compared to motorized private transport, the conversion of conventional to alternative powertrain systems takes place to a lesser extent in vehicles for freight transport. In 2030 combustion engines will continue to be the dominant drive technology for road-bound freight transport in all scenarios, and also in 2030 the proportion of mileage driven by hydrogen-electric vehicles will still be very low. In 2050 an increase in alternative drive technologies can be seen in all scenarios, with conventional internal combustion engines still playing a major role. According to the model results, it makes sense to not convert some of the combustion-based vehicles and instead to run them on CO_2-neutral fuels (see Table 4) in order to reduce emissions. In the *Reference* scenario, for example, around 56 % of the mileage driven in 2050 will be covered by conventional drive technologies. A further 24 % of the mileage driven will be covered by hydrogen-electric vehicles, followed by trucks running on overhead contact lines (just under 20 %). In contrast to battery electric vehicles in motorized private transport, it is assumed that trucks running on overhead lines cannot be operated in a grid-supportive manner. Instead, their charging behavior is based on stored driving profiles.

Due to the assumed lack of acceptance to changes in large infrastructures in the *Non-Acceptance* scenario, the use of overhead contact-line trucks was excluded here. Pure battery use was considered for smaller delivery trucks (e.g. for parcel delivery) and city buses, but not for commercial trucks covering long distances. Although promising developments are also being tested in this area, the data basis is currently still insufficient, so that these concepts were not considered. This leads to an intensive use of hydrogen in heavy-duty traffic in the *Non-Acceptance* scenario.

The mix of liquid fuels used for all road transport is shown in Table 4. In 2030 fossil fuels (or fossil fuel contents) dominate in all scenarios. Here it is important to note that no mandatory blending of biofuels was assumed in the model simulations. Greater differences can be observed when comparing the scenario results in the year 2050. While fossil fuels still account for around 50 % in the *Reference*, *Non-Acceptance* and *Sufficiency* scenarios, the corresponding value is much lower for the *Persistence* scenario.

Overall, it can be seen that in the scenarios with a target of 95 % reduction in energy-related CO_2 emissions, a considerable share of the available fossil fuels is used for the heavy-duty transport.

Table 4: Overview of liquid fuels used for transport in 2030 and 2050 in the four scenarios studied (individual and freight transport, air transport, inland waterways and fuel-based rail transport).

	Liquid Fuel Mix in %	Fossil	Power-to-Fuel	Biomass
2030	Reference	100%	0%	0%
	Persistence	99%	1%	0%
	Non-Acceptance	95%	0%	5%
	Sufficiency	94%	0%	6%
2050	Reference	56%	19%	25%
	Persistence	9%	83%	8%
	Non-Acceptance	52%	23%	25%
	Sufficiency	49%	12%	39%

3.2.3 Building Heat

The provision of space heating and domestic hot water accounted for around 30 % of total final energy consumption in Germany in 2018. A key measure to reduce emissions in this area is to lower the heating requirement. This can be achieved by renovating the building envelope of existing buildings to make them more energy efficient and by reducing the heated living space. This would require changes in behavior, reflected, for example, in a decrease in the specific living space per inhabitant. The second important measure in the building sector is the use of heating technologies with lower specific CO_2 emissions. The modeling results based upon the implementation of these measures for the four scenarios studied are presented below.

Building Energy Renovation

Energy refurbishments in the building stock are represented in the model by three different degrees of energy renovation. “No refurbishment” is based on the current state of buildings from 2011, which have undergone no refurbishment. The second category called “Full refurbishment” is based on the specifications of the Energy Saving Ordinance (EnEV) and the third category “Full refurbishment plus” is based on the passive house standard [37, 38]. The number of buildings undergoing energy refurbishment each year is determined by the optimization algorithm in all of the scenarios except for *Persistence* scenario. Among other restrictions, the *Persistence* scenario assumes that a maximum of one percent of the building stock is refurbished per year. In the other three scenarios, however, the rate of refurbishment can be freely determined. The number of non-refurbished or energetically refurbished buildings directly influences the useful heat demand to be met. Table 5 provides an overview of the corresponding heating requirements and the proportion of refurbished buildings in 2030 and 2050 for the four scenarios examined. It also shows the average rate of refurbishment over the period analyzed.

Table 5: Net energy demand for space heating and domestic hot water for the four scenarios considered. In addition to the degree of refurbishment, the energy demand depends on the weather data set which is taken into account (weather year).

	Useful heat demand in TWh_{th}		Share of refurbished buildings in %		Rate of refurbishment in %
	2030	2050	2030	2050	2020-2050
Reference	725	604	51	79	1.4
Persistence	720	631	52	74	1.0
Non-Acceptance	726	593	51	83	1.5
Sufficiency	759	576	43	88	1.7

The results show that building energy refurbishment plays a role in the energy system transformation in all scenarios. According to the results, the percentage of refurbished buildings in the building stock will be between 43 % and 52 % in 2030 (today's share: 40 %). Despite this increase, the useful heat demand can only be reduced slightly by 2030. This can be attributed in part to the increasing number of buildings over the years. In addition, the simulations were carried out using different data sets (weather years), and the data set used for the year 2030 has a comparatively low mean outdoor temperature and solar radiation, which corresponds to a comparatively high space heating requirement. Due to the assumed decrease in consumption, the results from the *Sufficiency* scenario show that the CO_2 targets can also be achieved for the building sector with much less effort compared to other scenarios. This is reflected in the lower percentage of refurbished buildings calculated in the model for the year 2030.

A different picture emerges for the year 2050, when the *Sufficiency* scenario has the highest proportion of refurbished buildings. This follows the scenario's assumption that supportive efforts are made in politics and the population to lower emissions by reducing energy consumption. For this purpose, it was assumed that the minimum rate of refurbishment increases to two percent per year between 2030 and 2040. Because of this, the *Sufficiency* scenario shows the greatest reduction in useful heat demand among the four scenarios. In the *Reference* scenario, on the other hand, the optimization specifies an annual refurbishment rate that is up to twice the current level, so that the average over the period under consideration is 1.4 %. The *Non-Acceptance* scenario shows a similar development. Here a slightly higher rate of refurbishment is achieved, due to the restrictions set in other sectors. In the *Persistence* scenario, the rate of refurbishment remains fixed at a value of 1.0 % even after 2030. As a result, the useful energy demand is almost 30 TWh_{th} higher in 2050 compared to the *Reference* scenario.

Across the four scenarios, a consistent picture emerges, which emphasizes the role of building energy refurbishment. The results show that a large part of the building stock should be refurbished in order to achieve the emission reduction target of 95 % compared to 1990 at optimal costs. The annual rate of refurbishment varies between about 1.0 % and 2.1 %, averaging about 1.6 % in the *Reference*, *Sufficiency* and *Non-Acceptance* scenarios respectively.

Technologies for Heat Supply

The second important measure to reduce CO_2 emissions in buildings is to replace gas or oil-fired boilers with technologies having lower specific emissions (in relation to the amount of heat provided). Heat pumps are especially suitable here, since a large percentage of the required energy is taken up from the surrounding environment (e.g. outside air, soil, building exhaust air). Other possibilities are the use of biomass in pellet boilers, solar thermal systems or even the use of fuel cells or combined heat and power plants, which make more efficient use of the energy carriers than a combustion boiler.

In the model, the building's heat demand is covered by a heat generator or a heat grid. A variety of technologies are used to supply heat in heat grids. These include large heat pumps, combined cycle gas turbine plants (CCGT) with heat recovery (combined heat and power generation, driven either by heat or electricity depending on the current requirements), condensing boilers, solar thermal systems and electrode boilers. Another possibility is to install large storage tanks (hot water tanks), which open up the flexibility options in the supply. The technologies for the supply of heat in buildings are shown for 2030 and 2050 for the four scenarios in Figure 20.

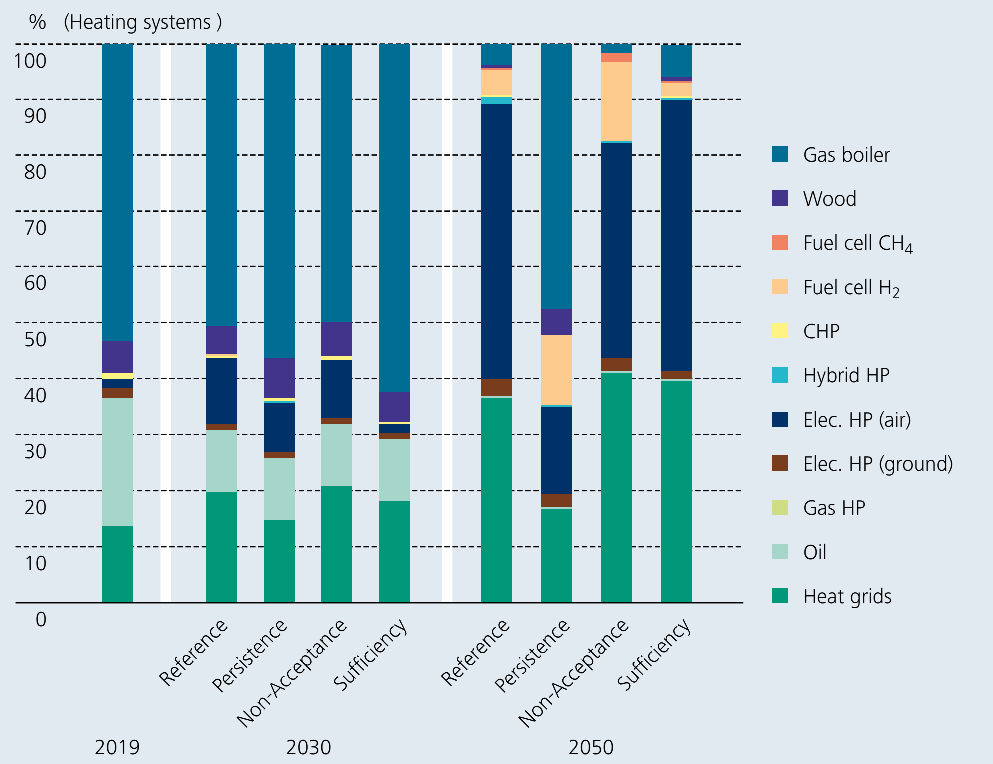


Figure 20: Share of heating systems that supply space heating and domestic hot water in buildings in 2030 and 2050 for the four scenarios examined. Solar thermal energy and heating rods can be used additionally, but are not shown here (HP: heat pump).

Today, space heating and domestic hot water are primarily provided by oil and gas boilers, which account for around three quarters of all heat generators in Germany. Their share decreases with time across all scenarios, yet still will be about 61 % in 2030 in the *Reference* scenario. This decline is largely compensated by electric heat pumps and connections to heat grids, which will cover 12 % and 20 % of the heat demand respectively in 2030. In the *Persistence* scenario, the share of heat pumps and connections to heat grids is lower, at 10 % and 15 %, respectively. This is due to the boundary conditions for this scenario which are explained in Chapter 2.3.

In 2050, the heat supply in the *Reference*, *Sufficiency* and *Non-Acceptance* scenarios will be provided in about 38 % of all buildings by heat grids. Electric heat pumps will be installed in 42 % to 54 % of the buildings. In total, these technologies thus cover a large part of the demand for space heating and domestic hot water. The dominance of these technologies in the three scenarios is mainly due to the high conversion efficiency of heat pumps, a key technology also in heat grids. The average annual performance factor of heat pumps of around 3.4 indicates that a large amount of environmental heat is used, which has an impact on the resulting emissions. In addition, heat pumps can be operated in combination with thermal energy storage systems to support the grid and thus contribute to load balancing in the electricity system. Thus, on days with plenty of sun or wind, electricity from renewable energy sources can be used to raise the temperature level in the thermal energy storage by means of heat pumps. The heat stored in this way can be used during periods of low availability of renewable energy and thus reduce the electricity load. In heat grids, combined cycle gas turbine (CCGT) plants are operated during low renewable availability, thus contributing to load balancing. If required, decoupled heat can be used directly or rather to charge large heat storage units. All in all, multi-modal heat grids, i.e. grids fed from different generators in combination with large heat storage facilities, have proven to be an effective measure for providing flexibility and load management in dense urban areas.

The use of biomass for space heating and domestic hot water will play almost no role in 2050. From a systemic point of view, it appears to be more cost-effective to use biomass for the provision of process heat and for the production of liquid fuels or biogas (see Section 3.2.1 and Table 4 and Table 6) and to rely instead on electricity-based technologies and district heating for space heating.

The *Non-Acceptance* scenario shows that a restriction of wind energy expansion and the associated higher expansion of photovoltaic systems leads to a larger share of hydrogen-based technologies in the consumption sectors. For example, in 2050 almost 15 % of households will be supplied by a fuel cell heating system to cover their heat requirements (CH_4 or H_2-based), which equates to 105 TWh_{el} of electricity generation in 2050.

Based on the boundary conditions in the *Persistence* scenario, the share of conventional heat generators will be at least 50 % in 2050, i.e. half of all buildings will be heated with a gas boiler. Thus, the proportion connected to the heat grid in 2030 in the other scenarios, is first reached in 2050 in this scenario. The share of air-source heat pumps is also only 18.5 %. Due to the boundary conditions set, it is much more difficult in this scenario to achieve the emission targets by means of reducing the useful heat demand and by changing the composition of the heating technologies. Accordingly, CO_2-neutral synthetic energy carriers generated from renewables must be used to a greater extent (similar to the transport sector). See Table 6.

The part of the heat demand not covered by heat pumps and heat grids is supplied by a mix of different heat generators, with gas boilers and fuel cells making up the largest share. In 2050 only a small percentage of the gas used will still come from fossil sources. Also, the emissions from the gases used for this purpose will decrease due to the reduced use of fossil natural gas and the simultaneous increase in biogas, synthetically produced methane and hydrogen. The composition of gaseous energy carriers in the grid is shown in Table 6 for the years 2030 and 2050.

Table 6: Mix of gaseous energy carriers in the grid in the four scenarios for the years 2030 and 2050.

Gas Mix in %		Natural Gas	Biomass	Power-to-Gas
2030	Reference	90%	6%	4%
	Persistence	87%	9%	4%
	Non-Acceptance	93%	4%	3%
	Sufficiency	93%	4%	3%
2050	Reference	16%	67%	17%
	Persistence	34%	39%	27%
	Non-Acceptance	31%	64%	5%
	Sufficiency	36%	47%	17%

Across all scenarios, it can be stated that in combination with energy refurbishments, an extensive changeover from the use of conventional heat generators to heat pumps and heat grids is an essential cornerstone of a cost-optimized transformation of the heating sector.

Energy Mix for Building Heat Supply

For the provision of space heating, the model distinguishes between two systems, which are characterized by different temperature levels: Radiator and panel heating systems (e.g. radiant floor heating). The latter requires a lower supply temperature because the heat is transferred to the room over a larger surface area. The conversion from one type of heating system to another is handled in the optimization. Depending on the type of system, such a refurbishment can have a greater or lesser effect on the conversion efficiency of the entire heating system.

With a share of around three-quarters, radiator heating systems account for the majority of the heating systems in German buildings today. By 2050, their share will decline continuously – and the more ambitious the boundary conditions are in the respective scenarios, the faster this will happen. As a result, the heat supply will become more efficient, especially in heat pump systems. Figure 21 shows the quantities of heat provided per technology for the years 2030 and 2050. In addition, technologies that supplement the heat supply, such as solar thermal systems or heating rods, are also listed.

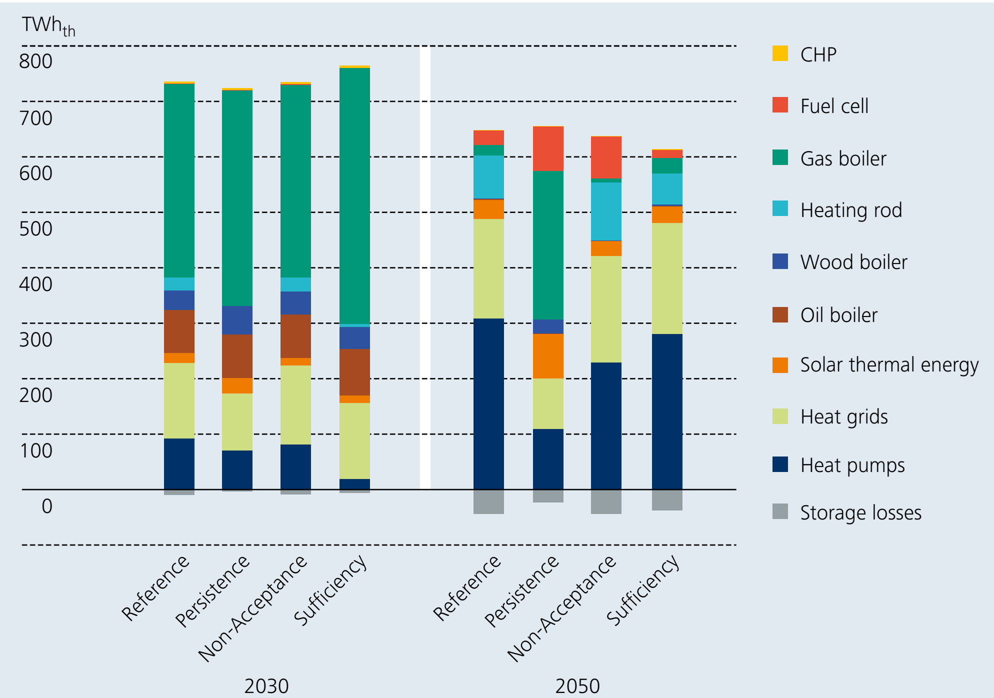


Figure 21: Heat supply in the building sector according to heating technology for the four scenarios for 2030 and 2050. Storage losses are shown negatively (CHP: combined heat and power unit).

In the *Reference* scenario in 2030, a large part of the heat will still be transmitted by radiator heating. Gas boilers will provide 50 % and oil boilers 11 % respectively. At the same time, the simulation results show an increase in panel heating systems and in heat generators with lower CO_2 emissions such as wood boilers, heat grids, heat pumps and solar thermal systems. Heat pumps in particular benefit from the lower supply temperature of the panel heating systems and thus the higher conversion efficiency.

The further conversion from radiator to panel heating becomes apparent after 2030, with the share of panel heating rising to almost two thirds by 2050 in the *Reference* scenario. As shown in Figure 21, a large part of the heat demand is covered by heat pumps and heating grids. In addition, other technologies that can be used to balance the residual load are also gaining in importance. These include, for example, heating rods (used on days with high feed-in from variable renewable energy) or fuel cells (used more on days with low feed-in from variable renewable energy). This is evidenced, for example, in the *Non-Acceptance* scenario, in which the electricity generation by fuel cells partially compensates for the reduced expansion of wind energy.

In the *Persistence* scenario it was specified that, in addition to the continued use of conventional technologies, no technologies that promote flexibility such as heating rods are to be used. Therefore, these do not represent an option for balancing the residual load. This restriction is partly compensated by using solar thermal systems to a greater extent. For example, the heat generated from solar thermal systems in 2050 will be just under 80 TWh_{th} compared with around 45 TWh_{th} in the other scenarios. This corresponds to an installed capacity of around 110 GW_{th} for solar thermal systems in the *Persistence* scenario in 2050, of which a good two-thirds of the systems are in buildings and almost one-third feed into heat grids; this ratio is similar in all scenarios. In addition, all scenarios include solar thermal energy systems for processes in trade and industry with an installed capacity of around 15 GW_{th}.

3.2.4 CO_2 Reduction by Sector

In order to make comparisons with sector-specific observations from other studies, the emissions from the areas of application electricity, transport, building heating and process heating (as broken down in this study) were converted into the transport, building, industry and energy sectors [27].

The energy sector describes the emissions resulting from the combustion of fossil fuels in power plants serving the public electricity and heat supply and from pipeline compressors and refineries as well as other fugitive emissions from the energy economy. This means that the figure also includes emissions caused by electricity consumption in private households, transport, industry and in the tertiary (TCS) sector. Accordingly, all emissions for electricity generation calculated with the model are allocated to this sector. The transport sector describes emissions caused by domestic road, rail and air transport as well as inland and coastal shipping. The buildings sector includes emissions caused by the use of fuel for space heating and hot water in households, in the tertiary sector, industrial and public buildings. Finally, the industrial sector includes all emissions caused by the provision of process heat (including steel production). Process-related emissions, on the other hand, are not shown, in line with the balance sheet limit used as a basis for the model. Figure 22 shows the resulting CO_2 emissions per sector from 2020 to 2050 for the *Reference* scenario.

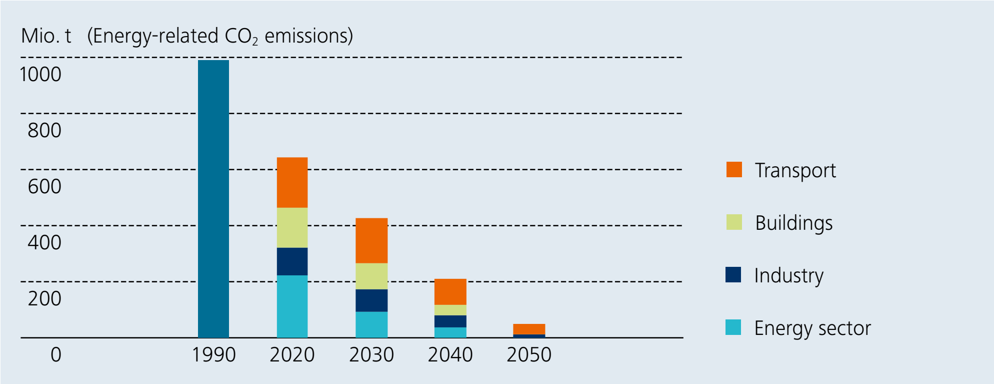


Figure 22:
Energy-related CO_2 emissions for the Reference scenario in million t CO_2 after breakdown into the sectors of transport, buildings, industry and energy industry

According to calculations with this model, the energy sector shows the largest reductions up to 2030, while emissions from the transport sector will decline comparatively less by 2030.

The development of the specific CO_2 factors of the various energy carriers is also shown for the *Reference* scenario in Figure 23.

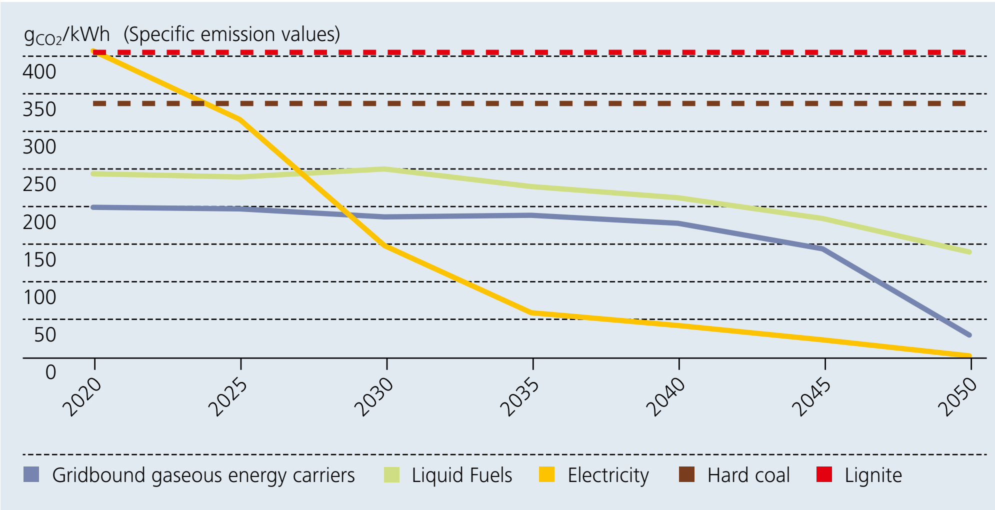


Figure 23:
Development of the CO_2 factors for electricity, hydrogen, grid-bound gaseous energy carriers, liquid fuels, lignite and hard coal

The development of the CO_2 factors shown in the results of the model underlines the energy sector's strong contribution to emission reductions, since the CO_2 factor for electricity in particular already shows significant reductions by 2030. In 2050, electricity generation is about 3 gCO_2/kWh_{el} and thus almost completely free of fossil fuels. The CO_2 factors for gaseous energy carriers in the grid and for liquid fuels also change over time, but with a significant delay compared to electricity. From 2020 to 2050, the CO_2 factor of liquid fuels decreases from 242 gCO_2/kWh to 140 gCO_2/kWh and of gaseous energy carriers in the grid from 199 gCO_2/kWh to 29 gCO_2/kWh in the scenario described here.

This evaluation underlines the major role that sector coupling plays in the energy transition. Successive reductions in the use of fossil fuels in the application areas of heat (buildings, processes) and transport, combined with a greater use of electricity, and an accelerated reduction of specific emissions in electricity generation, appear to be the most cost-effective way to achieve the desired reduction targets for CO_2 emissions in energy supply.

3.3
Complete Reduction of Energy-related CO_2 Emissions

In addition to the previous scenarios, this section presents the further steps necessary to move from a far-reaching (minus 95 % relative to 1990) to a complete (minus 100 %) reduction of energy-related CO_2 emissions. This means that the energy consumption of all sectors is based 100 % on renewable energy sources used either domestically or abroad[13].

In order to analyze the technical feasibility and the effects of a complete reduction of energy-related CO_2 emissions, two model calculations are carried out, which are derived from the previously considered scenarios. The first model investigates a complete reduction of energy-related CO_2 emissions by 2050; otherwise, the boundary conditions of the *Reference* scenario are essentially used as a basis (hereinafter referred to as "*Reference100*"). The second model calculation is based on the boundary conditions of the *Sufficiency* scenario. It considers a strongly accelerated, complete reduction of energy-related CO_2 emissions by 2035 (hereafter referred to as "*Sufficiency2035*").

3.3.1 Complete Reduction of Energy-related CO_2 Emissions by 2050

A comparison of the scenarios *Reference* and *Reference100* shows that the primary energy demand in 2050 hardly differs between the two cases. Accordingly, the use of natural gas, oil and hard coal in 2050, which in the *Reference* scenario totals 190 TWh, must be replaced. Imports of electricity and biomass remain at a similar level in both scenarios due to the set boundary conditions (biomass availability and grid expansion to neighboring countries). Around 80 % of the energy that is no longer available in the form of fossil fuels in *Reference100* is compensated by an increased electricity generation from solar and onshore and offshore wind. Figure 24 shows a comparison of the installed power plant capacities for the generation of electricity from variable renewable energy sources (wind, sun) in the years 2030 and 2050.

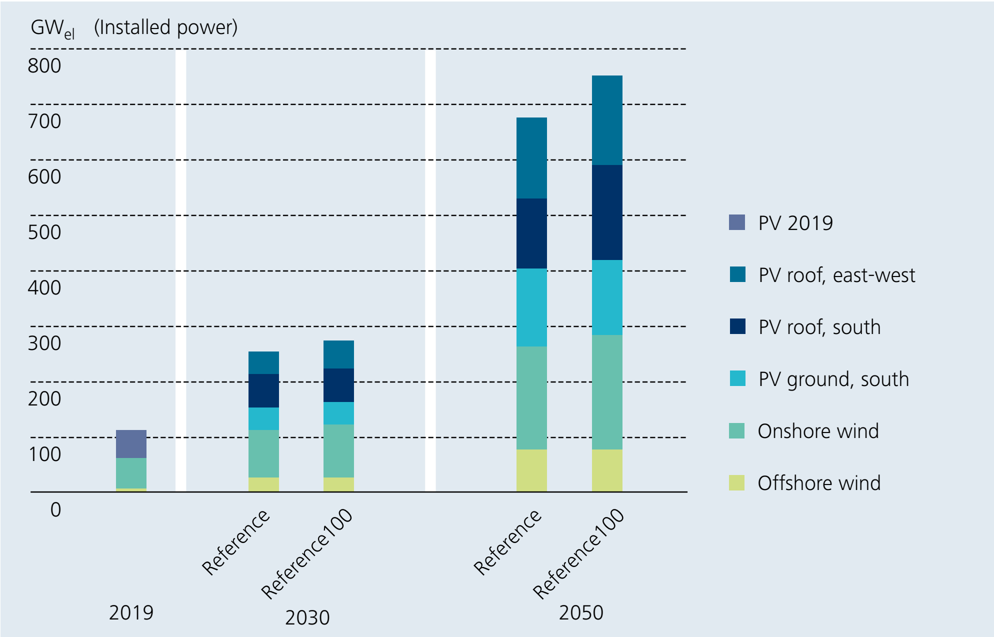


Figure 24: Installed power plant capacity for electricity generation from variable renewable energy sources (wind, sun) in 2030 and 2050 for the *Reference* and *Reference100* scenarios

13 The capture and storage of CO_2 underground (Carbon Capture and Storage, CCS) is not examined in this study, as there is currently no legal basis for its implementation in Germany.

The differences shown in the installed capacities for electricity generation from variable renewable energy sources are still negligible in 2030. This is because the reduction targets of the two scenarios do not differ significantly up to this year. In 2050, the *Reference100* scenario has a total installed capacity of 734 GW_{el}, which is around 70 GW_{el} greater than the *Reference* scenario. About half of this additional capacity is accounted for by wind and the other half by photovoltaic plants.

The required higher capacity of renewable power plants for electricity generation leads to a correspondingly greater need for flexibility in order to effectively incorporate the fluctuating electricity generation into the energy system. This is evidenced, for example, by the installed capacity of short-term energy storage facilities and electrolysis plants. At 240 GWh_{el}, the capacity of short-term energy storage facilities in 2050 is around 30 GWh_{el} higher in the *Reference100* than in the *Reference* scenario. The installed capacity of electrolysis plants is around 50 GW_{el}, or about 12 GW_{el} higher, respectively. In 2050, therefore, hydrogen production in *Reference100* is about 30 TWh_{H2} greater than in the *Reference* scenario.

However, this additional plant capacity and the domestic production of hydrogen are not sufficient to fully compensate for the loss of fossil fuels. For example, the imports of synthetic liquid fuel will almost double, reaching 55 TWh. In the *Reference100* scenario, the amount of imported hydrogen will increase by around 30 TWh_{H2} to 146 TWh_{H2} in 2050. The sectors in which the additional hydrogen (60 TWh_{H2} in total) is used and how the hydrogen is provided are shown in Figure 25 for the year 2050.

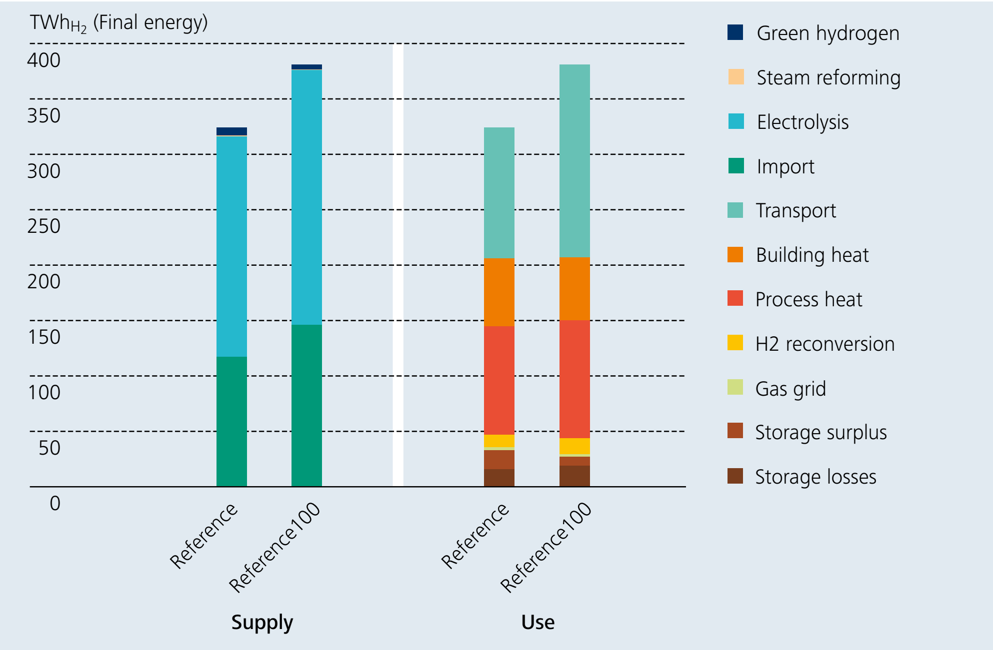


Figure 25: Hydrogen supply and use for the *Reference* and *Reference 100* scenarios for 2050

The results show that most of the produced hydrogen is used in the transport sector and in industry. Thus, the complete conversion in motorized private transport from conventional combustion engines to electricity-based alternatives takes place in the *Reference100* scenario two years earlier than in the *Reference* scenario. This means that more hydrogen-electric vehicles are on the road, increasing the hydrogen demand by 56 TWh_{H2} in 2050. The main difference lies in the conversion of the freight transport, however. For example, the share of hydrogen-based heavy good vehicles increases from around 40 % in the *Reference* scenario to twice that in the *Reference100* scenario. (The remaining 20 % of the transport fleet is made up of heavy good vehicles running on overhead contact-lines). This changeover shows that in order to achieve a complete reduction of energy-related CO_2 emissions in all sectors, it is more cost-effective to replace the remaining internal combustion engines in freight transport with hydrogen-electric powertrains and to use domestically produced or imported hydrogen than to operate internal combustion engines with synthetic liquid fuel. This statement for the year 2050 naturally has a high degree of uncertainty, since it depends decisively on the import prices for synthetic energy carriers produced abroad from renewable electricity.

A further percentage of the produced hydrogen is used in the industrial sector. Since coal is substituted completely by hydrogen in steel production, more hydrogen is used in the *Reference100* than in the *Reference* scenario. At the same time, hydrogen fuel cells are used to provide space heating and domestic hot water, which is the third highest demand in both scenarios, regardless of the CO_2 emissions target value (see Figure 25). A comparatively small proportion of the hydrogen is fed into the natural gas grid and then converted back into electricity in gas turbines. The remaining quantity represents storage losses or the stored carryover to the following year.

While the absolute value of the hydrogen supply differs in the two scenarios presented, the proportion from the different sources of production differs only slightly. For example, electrolysis in Germany accounts for about 60 % in each of the two scenarios and the import of synthetic hydrogen for almost 40 %. Steam reforming and biohydrogen will only play a minor role in 2050.

In summary, the comparison of the *Reference* and *Reference100* scenarios shows that in addition to a more extensive expansion of renewable power plants for electricity generation, the increased use of hydrogen plays a central role in reaching a 100 % reduction of energy-related CO_2 emissions by 2050.

3.3.2 Complete Reduction of Energy-related CO_2 Emissions by 2035

For a development of the German energy system that is compatible with a target of 1.5 °C, it would be necessary to completely reduce Germany's energy-related CO_2 emissions by 2035, based on Germany's remaining CO_2 budget [39]. The share of the remaining total budget available for the energy sector would then amount to about 6 billion tonnes. The following analysis examines a transformation path leading to a complete reduction of energy-related CO_2 emissions by 2035.

It is therefore assumed that the achievement of a climate neutral energy system within 15 years would only be feasible if the transformation path is supported by broad social consensus. Aside from this time scale, the *Sufficiency2035* scenario is essentially based on the assumptions of the *Sufficiency* scenario. Since these assumptions alone do not ensure the technical feasibility of climate neutrality by 2035, three further assumptions are made:

1. the use of coal for steel production will be substituted by hydrogen by 2035
2. the minimum load at which coal-fired power plants must operate will be reduced by half by 2035
3. the import of synthetic fuels will be possible from 2025, i.e. five years earlier than in the other scenarios

In carrying out the model calculations, the annual growth rates and expansion potentials of the technologies were not changed, nor were the rates of system replacements; for example, there was no obligation assumed to replace conventional heating boilers before the end of their service life. In this respect, the results can only provide a first indication of the implications that such an accelerated phase-out of fossil fuels would have.

Based on the given assumptions, it can be seen that a complete reduction of energy-related CO_2 emissions by 2035 is only possible if considerable quantities of CO_2-neutral energy carriers are available for import. This makes it possible to completely displace fossil fuels and reduce CO_2 emissions to zero by 2035. Compared to all other scenarios, the required import volume of synthetic energy carriers produced carbon-neutral is very high. This amount will then decline again by 2050 (see Figure 26). The maximum import volume is 570 TWh and occurs in 2035.

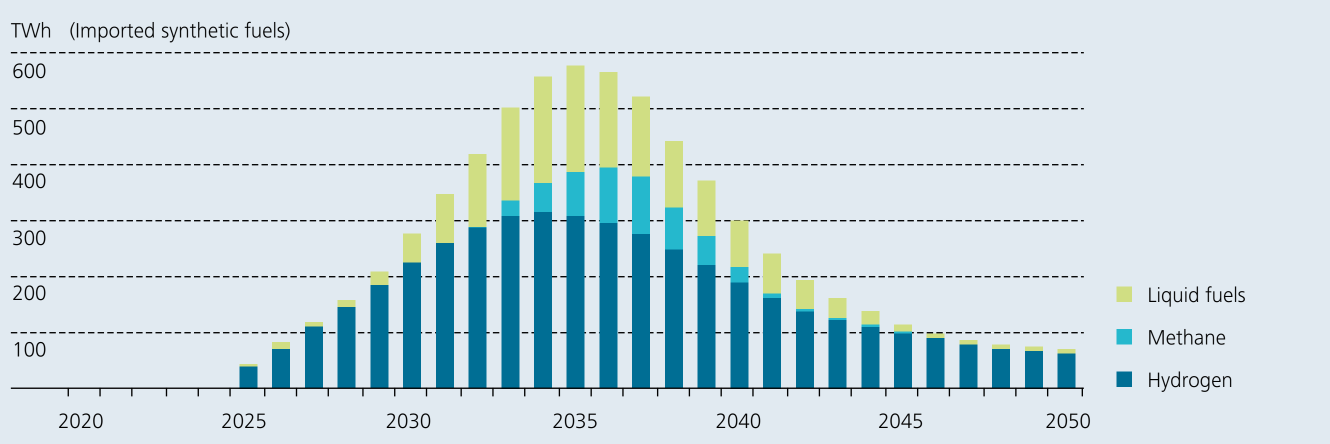


Figure 26: Time series of imported synthetic energy carriers from 2020 to 2050 in the *Sufficiency2035* scenario

After the initial increase in synthetic fuel imports, which are necessary to displace fossil fuels, a continuous reduction is evident, so that only about 70 TWh will be imported in 2050. This roughly corresponds to the import volume of the other scenarios in 2050, showing that the import of synthetic fuels in this scenario takes place despite the high energy prices, but is only a transitional solution on the way to CO_2 neutrality. Under the given assumptions it is more favorable to gradually reduce the high import volume in 2035 by installing renewable power plants to generate electricity and also plants to further convert it to other forms (e.g. electrolysis). An example of this development is the continued growth in the installed capacity of wind, photovoltaic and electrolysis plants after 2035 (Table 7).

Table 7: Installed capacity of power plants for the generation of electricity from variable renewable sources and electrolysis plants in the *Sufficiency2035* scenario.

Installed Plant Capacity in GW_{el}	2020	2025	2030	2035	2040	2045	2050
Wind	72	104	144	185	226	230	232
Photovoltaics	60	105	181	264	327	362	384
Elektrolysis	0	4	11	32	61	75	83

The correlations presented show that a complete reduction of energy-related CO_2 emissions by 2035 will require considerable efforts. Corresponding cost aspects are discussed in the following subchapter.

3.4
Cost Analysis

3.4.1 Total Cumulative Expenditure of the Energy Transformation

In the previous chapters, various possible transformation paths for the German energy system were presented. These consider distinct and broadly effective attitudes of society that are accordingly characterized by specifically defined boundary conditions. A cost optimization was carried out under the given boundary conditions. As explained in Section 2.1, the cumulative expenditure for conversion, expansion and operation of the entire energy system for the period 2020 to 2050, which consists of investments (CAPEX) and all costs (OPEX: energy carriers, operation, maintenance, transaction costs), is determined and minimized by the optimization calculations for each scenario. Depending on the scenario, this value can vary considerably. Figure 27 shows the differences between the scenarios and a Business-as-Usual (BAU) scenario. In the BAU scenario there is no system optimization, i.e. the current state of the energy system is maintained[14] and emissions are only slightly reduced by assumed efficiency increases (technology learning curves). Investments are made exclusively to replace systems at the end of their service life with similar systems.

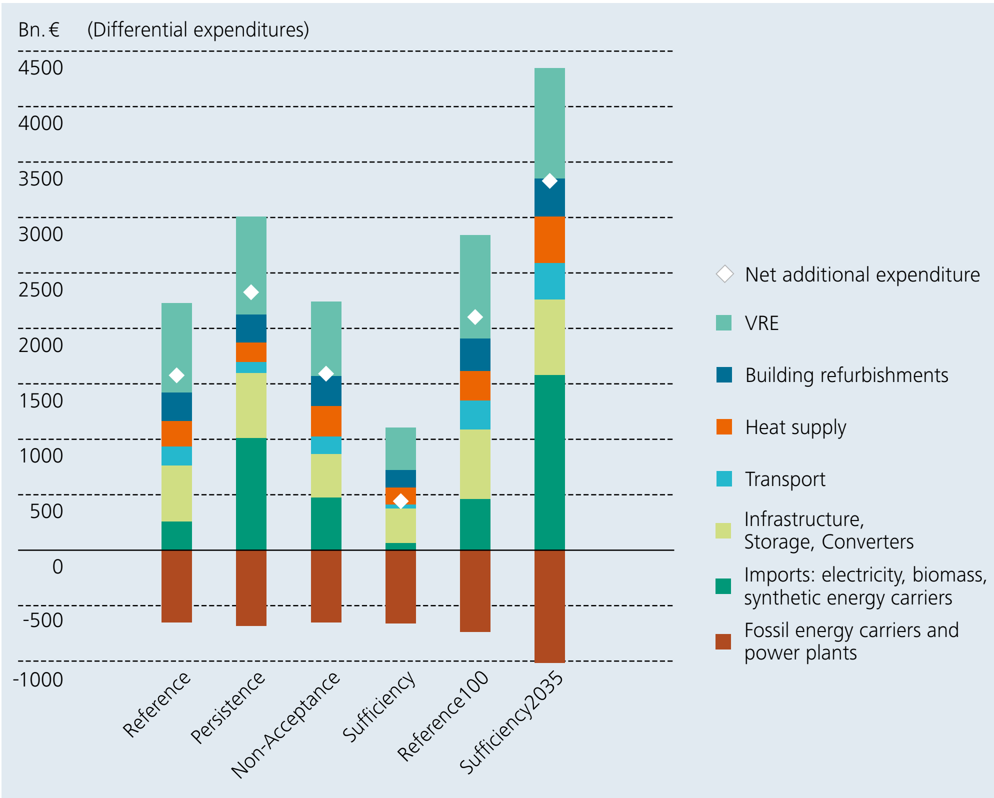


Figure 27: Differential expenditures for the various scenarios compared to the business-as-usual (BAU) scenario. The net additional expenditures per scenario (diamonds) are calculated by summing the positive and negative expenses (VRE: variable renewable energy).

Figure 27 shows a cost comparison for all the scenarios examined. It shows the additional expenses in comparison with the BAU scenario, differentiated according to the areas in which these additional expenses are incurred. Negative values describe reduced expenditure, in particular due to the lower costs of the import of fossil fuels in all climate protection scenarios. The sum of additional and reduced expenditures, represented by a hash mark, describes the net additional expenditures for the scenarios examined.

14 The legal decision to phase-out of nuclear power in Germany in 2022 is also taken into account in the BAU scenario.

These net additional expenditures amount to around € 1580 billion for the *Reference* scenario, € 2330 billion for the *Persistence* scenario, € 1590 billion for the *Non-Acceptance* scenario and € 440 billion for the *Sufficiency* scenario. These four scenarios are characterized by a reduction of energy-related CO_2 emissions by 95 % relative to the 1990 value. The diagram also shows the values for the scenarios which reach a complete reduction of energy-related CO_2 emissions. The corresponding value for the *Reference100* scenario, in which the complete reduction of energy-related CO_2 emissions is achieved by the year 2050, amounts to 2100 billion €. The value for the *Sufficiency2035* scenario, in which the complete reduction of energy-related CO_2 emissions is achieved already in 2035, is 3330 billion €. The average annual net additional expenditure over the entire period from 2020 to 2050 is € 14 billion annually for the *Sufficiency* scenario and € 107 billion for the *Sufficiency2035* scenario, respectively. The corresponding average values for the other scenarios with a 95 % reduction in energy-related CO_2 emissions by 2050 are around € 51 billion for the *Reference* and *Non-Acceptance* scenarios and around € 72 billion for the *Persistence* scenario. In relation to Germany's gross domestic product in 2019,[15] the net additional expenditures range from 0.4 % (*Sufficiency* scenario) to 1.5 % (*Reference* and *Non-Acceptance*) and around 2 % (*Persistence* and *Reference100*) and up to 3.1 % (*Sufficiency2035*). To give another impression, the annual amounts mentioned above are compared to the business turnover during Christmas time, which for 2019 in Germany was[16] just under € 102 billion, i.e. about twice the average net annual expenditure for the energy system transformation in the *Reference* and *Non-Acceptance* scenarios.

When compared to the BAU scenario, the *Reference* scenario is used to illustrate the main contributions leading to additional expenditures. At € 804 billion, the highest additional expenditure is used for investments in power plants that generate electricity from variable renewable energy sources. The additional expenditures for the expansion of infrastructure (e.g. grids), storage technologies and converters for the production of synthetic chemical energy carriers from renewable electricity (Power-to-Gas, Power-to-Fuel) total about € 500 billion. The third-largest additional expenditure of around € 255 billion is attributable to the energy refurbishment of the building sector. This includes the expenditures for converting radiator heating systems to low-temperature (panel) heating systems, which will enable an even more efficient use of heating technologies, especially heat pumps. Furthermore, in the scenarios in which an emission reduction is taken as a basis, the import of synthetic fuels from abroad causes additional expenditures. This expenditure amounts to € 260 billion in the *Reference* scenario. Finally, an additional expenditure of € 196 billion is attributable to conversion technologies in the consumption sectors for the provision of heat (building heating and industrial process heat) and € 170 billion in transport. In terms of the underlying cost trend, battery electric vehicles will achieve cost parity with conventional combustion vehicles as early as 2028, which is why the additional expenditure in the transport sector is primarily attributable to freight transport.

15 Germany's gross domestic product in 2019 was € 3436 billion. See e.g.: https://de.statista.com/statistik/daten/studie/1251/umfrage/entwicklung-des-bruttoinlandsprodukts-seit-dem-jahr-1991/

16 See https://de.statista.com/statistik/daten/studie/2750/umfrage/weihnachtsumsaetze-des-einzelhandels/

The differences in the composition of costs in the *Non-Acceptance* scenario and the *Reference* scenario differ only slightly, although the costs of importing synthetic fuels are also slightly higher in the *Non-Acceptance* scenario. The *Sufficiency* scenario has the smallest overall difference. At just under € 440 billion, this is around 30 % of that of the *Reference* scenario and 20 % of the *Persistence* scenario. The decrease in consumption assumed in the *Sufficiency* scenario leads to a reduction of all cost components (see Figure 27), which makes the savings in fossil fuels more significant. For example, the savings in the *Reference* scenario amount to around 30 % of the additional costs shown, whereas in the *Sufficiency* scenario these savings amount to 40 %.

In the *Reference100* scenario, a complete reduction in energy-related CO_2 emissions by 2050 was set as the boundary condition. When looking at the differences, it becomes clear that the shares of the individual cost items in the cumulative expenditures are almost the same as in the *Reference* scenario. This means that in the *Reference100* scenario the main trends of the *Reference* scenario are adopted and reinforced in order to displace the remaining fossil energy sources. Despite the more ambitious CO_2 reduction target, the net additional expenditures of the *Reference100* scenario are lower than those of the *Persistence* scenario. This result makes it clear that, from a cost perspective, the insistence of conventional technologies (especially combustion technologies in the transport and building heating sectors) means a considerable additional expenditure is needed to achieve the climate protection targets.

Finally, a complete reduction of energy-related CO_2 emissions by 2035 was considered in the scenario *Sufficiency2035*. Here the decrease in energy consumption, assumed in the *Sufficiency* scenario, was adopted. The net additional expenditure of € 3330 billion is more than double that of the *Reference* scenario and indicates that a complete reduction of energy-related CO_2 emissions by 2035 is associated with considerable additional expenditure, also from a cost perspective. This can be explained by using the example of imports of synthetic energy carriers. These represent the largest block of costs in this scenario (see Figure 27). For example, around 570 TWh of synthetic fuels are already imported in 2035 in this scenario, while the import volumes in the other scenarios are still comparatively small in 2035 and increase continuously until 2050 (see Figure 12 and Figure 26). Thus, the volume of synthetic fuels imported in the *Sufficiency2035* scenario in 2035 is similar to that in the *Persistence* scenario in 2050. A comparison of the import volumes over the entire period under consideration shows that they are almost a third higher in the *Sufficiency2035* scenario than in the *Persistence* scenario. This leads to correspondingly higher costs, since the assumed import prices of synthetic fuels in 2035 are on average 45 % higher than in 2050. Corresponding cost reductions over time also apply to many technical components, especially those that are still in the early stages of market introduction and where significant cost reductions can still be expected due to further technological development and industrial production. Since the switch to a complete reduction of energy-related CO_2 emissions by 2035 occurs earlier than in the other scenarios, the overall costs are higher over the entire period.

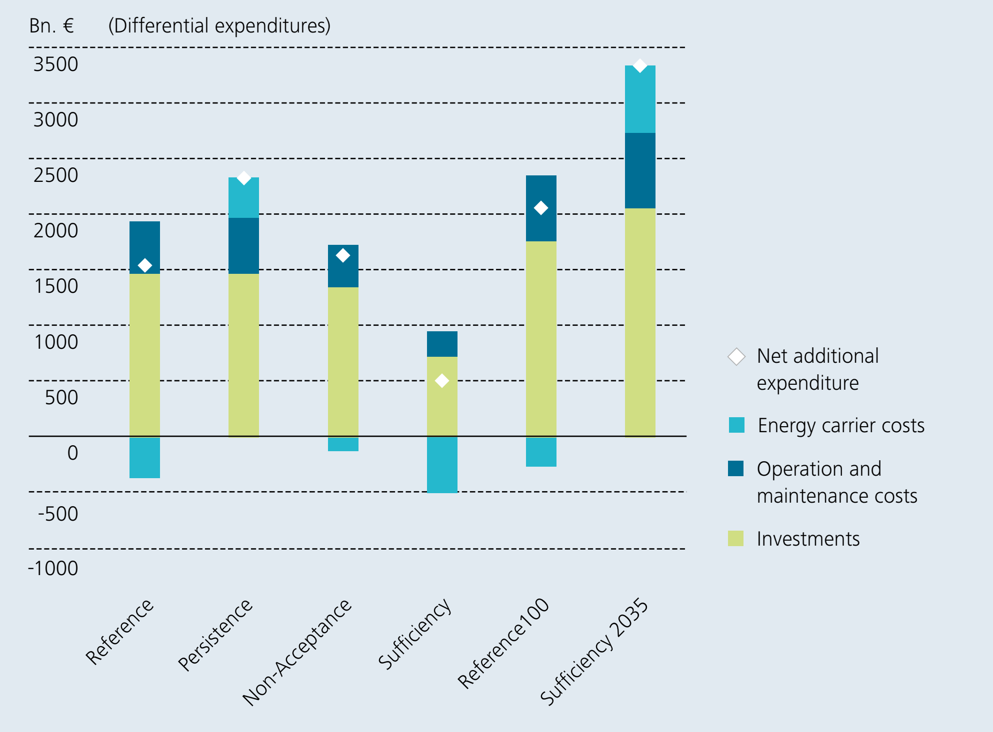


Figure 28: Cumulative expenditures over the entire period of consideration (2020 to 2050) for all scenarios examined, separated into investments (including replacement investments and capital costs), other operating and maintenance costs and costs of the energy carriers (in € billion).

Figure 28 shows an overview of the expenditures incurred from 2020 to 2050 for all energy carriers (both fossil and imports produced with renewable energy), operating and maintenance costs, and investments (including replacement investments and capital costs). Here, too, positive shares show the additional expenditure and negative shares show reduced expenditure, compared to the BAU scenario. The net additional expenses are marked by the hashes and the values are identical to those in Figure 27.

The results show that the additional expenditure for investments is between 63 % and 75 % in almost all scenarios. These investments are necessary to restructure the energy system. When the transformation is (largely) completed in 2050, the investments will decrease significantly, since from then on only replacement investments have to be made.

The cost analysis carried out does not provide a complete picture of total social (or economic) costs for two reasons:

- No external cost analyses have been carried out for any of the developments – neither for the BAU scenario nor for the climate protection scenarios, e.g. environmental or health costs arising as a result of one development or another.
- No macro-economic analysis was carried out that took value added and employment issues into account.

3.4.2 CO_2 Avoidance Costs

CO_2 avoidance costs can be calculated based on the results of the calculations performed. For this purpose, the net additional costs resulting for a scenario are divided by the CO_2 emissions avoided, compared to the BAU scenario. Figure 29 shows the corresponding values for all six scenarios, each shown as mean values for the years 2021 to 2030, 2031 to 2040 and 2041 to 2050, as well as the mean values for the entire period considered, from 2021 to 2050.

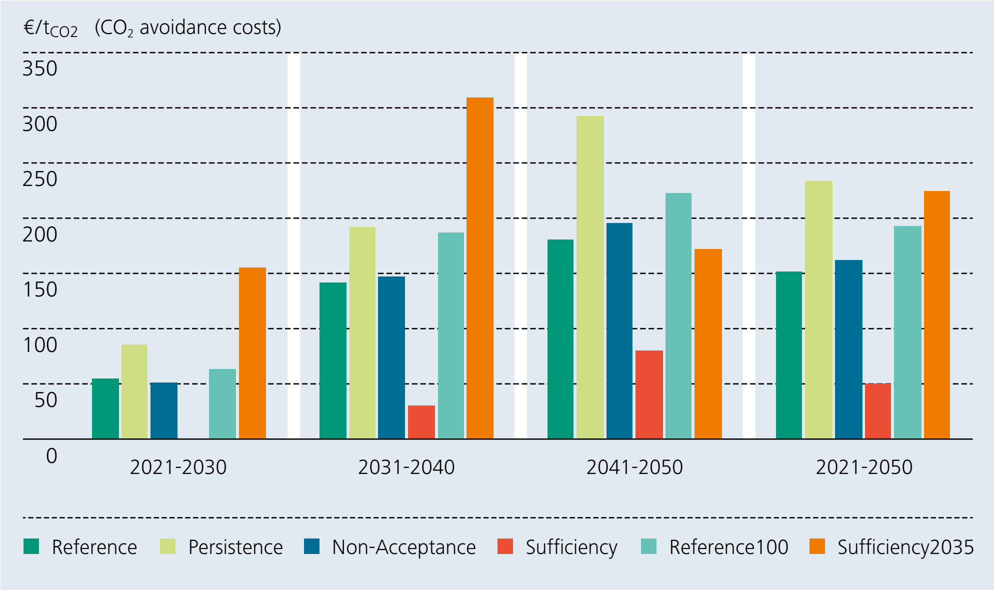


Figure 29:
CO_2 avoidance costs of all six scenarios examined. In each case, the mean values for the years 2021-2030, 2031-2040 and 2041-2050 are shown as well as the mean value for the entire period of consideration from 2021 to 2050.

With the exception of the *Sufficiency2035* scenario, the CO_2 avoidance costs in all other scenarios rise continuously over the three decades considered. This reflects the principle of mathematical optimization, i.e. first taking the most cost-effective avoidance measures and associated investments and then later implementing the more costly measures. In the *Sufficiency2035* scenario, the high quantity of imported synthetic energy carriers produced abroad with renewable electricity has a strong impact in the years from 2031 to 2040. The highest value of more than 300 €/tCO_2 occurs in this decade.

For the *Sufficiency* scenario, the CO_2 avoidance costs are by far the lowest. They average 50 € per tonne of CO_2, since the assumed reduction in energy demand due to behavioral changes is not associated with costs. For the *Reference* scenario, costs average around 150 €/tCO_2 and they rise over the three decades from around 50 €/tCO_2 in 2021-2030, to 142 €/tCO_2 in 2031-2040, to just over 180 €/tCO_2 in 2041-2050. Both the development and the values in the *Non-Acceptance* scenario have a similar order of magnitude as the *Reference* scenario. Over the entire period under consideration, the CO_2 avoidance costs average about 162 €/tCO_2 and are thus around 7 % higher than for the *Reference* scenario.

Based on the model results, a complete reduction of energy-related CO_2 emissions by 2050, as in the *Reference100* scenario, leads to CO_2 avoidance costs which are about 40 €/tCO_2 higher than in the comparable case yet with only 95 % emissions reduction by 2050. The highest costs are caused by a strong insistence on continuing to use today’s technologies, such as combustion technologies for heat provision and for the transport sector. In the *Persistence* scenario, the average CO_2 avoidance costs are 233 €/tCO_2, which are on the same order of magnitude as for the *Sufficiency2035* scenario.

The CO_2 avoidance costs given here demonstrate that changes in behavior in particular can have a considerable impact on the costs of energy transition. Collective societal behavior that saves energy and reduces emissions in large sections of society, e.g. induced by a change in values, would not only require less financial expenditure and less investment. It would also result in less expansion of renewable energy installations and other technical equipment in the future energy system, and thus presumably lead to greater acceptance of the changes accompanying the energy system transformation.

4 Conclusion

This study analyzed the influence that key societal behaviors and attitudes have on the progress of the energy transition and how this affects the necessary investments and costs of restructuring the energy system. The results show that it is technically and systemically feasible to reach the climate protection targets for the energy supply based on renewable energy sources. The model calculations, carried out on an hourly basis for the next thirty years, show that a secure energy supply throughout all consumption sectors is guaranteed for each hour, despite the high share of variable renewable energy sources in the electricity supply.

The different scenarios also illustrate that the differences in the expenditure and costs required to achieve the goals strongly depend on the framework conditions that are largely determined by societal behavior and attitudes. For example, if large parts of society were to change their behavior towards a more economical use of energy, this would have a considerable impact. As a result, the necessary amount of facilities for the conversion, storage, distribution and use of energy and the associated costs would be substantially lower than in all other scenarios considered. In contrast, adhering to the use of combustion-based technologies for the heat supply and transport would lead to substantially higher capacity requirements for renewable energy power plants and other related technical facilities. Also, the import of synthetic, chemical energy carriers, produced abroad on the basis of renewable electricity, would increase. Such persistent behavior would make the energy transformation more expensive. Strong resistance to the expansion of large infrastructures such as wind turbines and grids can be partially compensated by a modified path, albeit at slightly higher costs than in the case of cost-optimal development. Greater installments of photovoltaic systems and battery storage are elements of such a path.

An essential prerequisite for a comparatively cost-effective achievement of the climate targets is the continuous development of all relevant technologies for the conversion, storage, distribution, use and system integration of renewable energy. Only then will it be possible to achieve the projected reductions in costs and the increases in performance and service life. The study has also made it clear that the use of thermal and electrical storage systems in Germany is just as meaningful as the establishment of domestic production, processing and use of hydrogen in a wide range of applications. The development of domestic markets is important for all technologies and furthermore contributes significantly to successful technology development. On the one hand, markets for local manufacturers are created, and on the other hand, experience can be gained with the corresponding plants and their system integration. These are also essential prerequisites for achieving the desired improvements in costs and performance. At the same time, knowledge of these technologies and confidence in their reliability grows. This is also an important factor for export.

However, applied research and development does not end with component development; it can also make important contributions to increasing market integration. The concept of integrated photovoltaics is an example of this. It is foreseeable that a massive expansion of large open space photovoltaic systems could lead to conflicts and possibly to acceptance problems. On the other hand, the integration of photovoltaics into building envelopes, vehicle bodies and roads as well as agricultural land and water surfaces, will open up huge areas already used for other purposes for the dual use of solar power generation. Creating the appropriate products and solutions for these applications will be an important task in the further development of photovoltaics and will present new opportunities for domestic production. Electric heat pumps are another example. The investigations carried out underscore the important role of heat pumps in achieving a cost-effective transition in the heat sector. However, especially in urban areas regulations that limit the exploitation of heat sources are in place; noise emissions can also cause acceptance problems. Here, too, applied research and development in close cooperation with manufacturers and users is needed to address the arising problems and to develop new solutions. These are just two concrete examples of the many questions that need to be answered in order to develop customized solutions that are highly relevant for the successful implementation of the energy transition.

The future energy system will be characterized by a large number of interconnected systems. These will interact with each other and operate so as to provide as much dynamic support to the system as possible. Photovoltaic systems, heat pumps, stationary battery storage systems and charging stations for electric vehicles, but also technical systems, many in the small power range, are particularly important here. In the coming decades, the number of these systems is expected to reach the double-digit millions. Against this background, the development of solutions for efficient, stable and reliable system integration and operation of these many components plays a decisive role. This can be achieved only by using modern concepts from the information and communications technology (ICT). Application-oriented system research is just as relevant for the development of feasible solutions and business models as for energy system analysis, which serves as a compass for the successful development of the total energy system towards a climate-neutral energy supply.

With this study, we hope to contribute valuable input to the discussion on the feasibility of achieving a climate-neutral energy system, which is essentially based on two main pillars: renewable energy use and high efficiency in energy conversion and utilization.

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